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THE PRACTICAL TESTING
— OF —
DYNAMOS AND MOTORS.

$$n = \frac{e - Ir}{Z \frac{e}{p'} \times 10^{-8} \phi}$$

The Practical Testing

OF

Dynamos and Motors.

By CHARLES F. SMITH,
Assoc.M.Inst.C.E., A.M.I.E.E., Whit. Schol.

WITH OVER 80 ILLUSTRATIONS.

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PREFACE.

THIS little book is intended to serve as an elementary introduction to the study of continuous-current dynamo machinery.

The use of mathematics has been avoided as far as possible, results and inferences being discussed in connection with curves obtained in the experiments. The object in view throughout has been to encourage the student to carry out actual measurements on machines rather than to trust to calculations or formulæ.

It is hoped that the descriptions of the experiments comprised in the following pages may be found useful by students who are beginning the study of electrical machinery, by the rapidly increasing number of engineers who are only slightly acquainted with electrical work, but who are brought into contact with electrical machinery, and by the so-called "practical man" who is too "practical" to be satisfied by information and rules obtained at second-hand or from books, and who wishes to convince himself by actual trial of the truth of what he is told.

The author wishes to make acknowledgment to Mr. G. D. Aspinall Parr for kindly supplying curves from which Fig. 13 was drawn. He wishes also to take this opportunity of thanking his colleagues, Mr. U. A. Oschwald, B.A., and Mr. W. H. F. Murdoch, B.Sc., for their zeal in reading through the proofs and making many valuable suggestions.

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CONTENTS.

PAGE.

CHAPTER I.

General Purpose of Tests 1

CHAPTER II.

Measurement of Armature and Field Resistances—Comparison of Deflections—Potentiometer Method—Measurement of Low Armature Resistance by Thomson Bridge—Measurement of the Resistance of Field Windings—Variable Shunt Resistance—Determination of Temperature by Increase of Resistance—Temperature Rise in Magnet Winding 6

CHAPTER III.

Production of Electromotive Force in a Dynamo—Determination of Relation between Speed and Voltage of a Separately-excited Dynamo Without Load .. 23

CHAPTER IV.

The Magnetic Circuit—Magnetisation Curve—Calculation of Magnetisation Curve—Experimental Determination of Magnetisation Curve at No Load—Hysteresis—Residual Magnetism—Nature of the Magnetisation Curve—Magnetisation Curve of Dynamo with Varying Air-gap—Influence of Air-gap—Determination of Number of Ampere-turns from Curve—Magnetic Density—Power Spent in Excitation—Increasing the Voltage of a Dynamo 30

CHAPTER V.

Armature Reactions—Armature Ohmic Drop—Magnetic Reactions—Lead of Brushes—Sparkless Commutation—Determination of the Characteristic of a Separately-excited Dynamo—Variation in Exciting Current of a Separately-excited Dynamo to Maintain Constant Voltage—Magnetisation Curve of a Dynamo Under Load 50

CHAPTER VI.

PAGE.

Shunt-wound Dynamo—Determination of the Relation between Voltage and Speed of a Shunt-wound Dynamo—Characteristic of a Shunt-wound Dynamo—Total Characteristic—Conductivity Characteristic of Shunt Dynamo—Resistance Characteristic—Power Curves 68

CHAPTER VII.

The Series Dynamo—Characteristic of a Series-wound Dynamo—Resistance Characteristic—Conductivity Characteristic — Total Characteristic — Arc-lighting Dynamos—Effect of Variation of Speed—Series Characteristic of Arc-lighting Dynamo—Conditions for Self-excitation—Determination of the Critical Resistance from the Characteristic Curve of a Series Dynamo—Critical Current 81

CHAPTER VIII.

The Compound Dynamo—Long and Short Shunts—Characteristic Curve of a Compound Dynamo—Total Characteristic—Determination of Compound Windings—Calculations of Series Winding 94

CHAPTER IX.

Effect of Current in the Motor Armature—Torque of a Motor—Counter Electromotive Force—Methods of Field Excitation—Methods of Field Excitation in Shunt Motor—Methods of Field Excitation in Series Motor—Compound Motors—Starting Switch—Motor Speed Regulation—Speed Regulation by Alteration of the Field Strength—Determination of Variation in Speed of a Motor, with its Excitation—Regulation of the Speed of a Motor by a Resistance in the Armature Circuit—Determination of Dependence of Speed of a Motor upon its Voltage—Variation in Speed of Series Motor at Different Voltages and Loads—Relation between Direction of Rotation of Dynamo and Motor—Shunt Machines—Critical Speed—Series Machines .. 104

CHAPTER X.

Efficiency Tests of a Motor—Brake Tests—Brake Test of a Shunt Motor—Brake Tests of a Series Motor—Motor Characteristics—Characteristic of Series Motor at Constant Speed—Speed Curves of a Series Motor—Compound-wound Motor — Differential Winding — Determination of Number of Series Windings for Constant Speed Regulation—Cumulative Winding—Transmission Dynamometers—Cradle Dynamometer—Dynamo as Dynamometer 124

CHAPTER XI.

PAGE.

Efficiency Tests of a Dynamo—Direct Methods of Measuring Efficiency—Dynamo Driven by Motor of Known Efficiency—Indirect Methods of Measuring Efficiency—Two Coupled Machines Connected in Parallel—Determination of the Efficiency of Two Coupled Dynamos with Armatures Connected in Parallel—Determination of the Efficiency of Two-coupled Dynamos with Armatures Connected in Series—Swinburne's Electrical Method of Testing Efficiency—Electrical Separation of Losses in a Dynamo—Separate Determination of Core Losses—The Testing of Combined Engine and Dynamo Sets—Steam Consumption Test of Combined Engine and Dynamo Set—Efficiency Test of Combined Plant 144

CHAPTER XII.

Miscellaneous Tests—Insulation Tests—Determination of the Insulation Resistance of a Dynamo while Running—Determination of the Leakage Coefficient of the Magnetic Circuit of a Dynamo or Motor—Method of Measuring Voltage Round the Commutator—Regulation by Shifting Brushes—Effects Obtained by Shifting Brushes Round the Commutator—Observations of the Effect of Moving the Brushes of a Motor with Constant Excitation—Determination of Field Distribution .. 182

CHAPTER XIII.

Motor Generators and Boosters—Balancing Machines for 3-wire System—Determination of the Regulation of a Pair of Balancers for a 3-wire System—Efficiency of a Motor Generator—Boosters—Separately-excited Booster—Excitation of Separately-excited Booster to Maintain Constant Voltage—Series-wound Booster—Voltage Regulation by Series Booster 210

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THE PRACTICAL TESTING OF DYNAMOS AND MOTORS.

CHAPTER I.

PRELIMINARY.

General Purpose of Tests.—Experiments upon dynamos and motors are carried out for a variety of purposes. Usually they have only the general object of discovering whether a machine complies with a specification, or is able to supply a certain amount of power. By carefully watching the behaviour of a dynamo or motor when working under specially regulated conditions, it is, however, possible to learn a great deal about its construction and the merits of various points in its design.

Also, it is by actually experimenting with electrical machines, and determining the effects of different conditions, or methods of construction, that a sound knowledge of the underlying principles can be most surely gained.

In the following pages the methods of carrying out a number of typical tests and measurements are described, and some of the conclusions to be drawn from the results are pointed out. The experiments are arranged in a progressive series, so as to illustrate successively the functions of the various elements of the machines, and at the same time to suggest an outline of the tests which might well be carried out by a young engineer in order to make himself familiar with the behaviour of a dynamo or motor under different conditions.

It may be well to begin by drawing attention to a few rules and cautions of a practical nature which should be observed, especially by inexperienced experimenters.

Practical Hints.—(*a*) Draw a complete diagram of connections before making the actual connections for an experiment. Be sure that the actual connections correspond exactly with the diagram. Alter the diagram to suit any modifications in the connections found necessary when carrying out the experiment.

(*b*) Use thinner wires for connections to voltmeters, and in branch connections in which there is only very small current. This rule is superfluous in cases where large currents flow in the main circuit, as in such cases it is obviously more convenient to use thinner wires where possible. The same rule should, however, also be carried out in cases where a small wire would suffice for the main current, because the various connections can be more rapidly traced out, and mistakes are more easily avoided. In the diagrams of connections given later, the distinction between main conductors and branch connections is indicated by the use of thick and thin lines.

(*c*) Always insert a switch in the main circuit, even in cases where it is easy to start and stop the machine.

(*d*) Remember that the resistance of both the armature conductors and field windings of a dynamo or motor increases as they become heated during a run. In a machine which has been standing the resistance is therefore lower than when the machine is actually undergoing a test.

(*e*) When the reading of any instrument is not the actual value of the quantity measured, record the actual readings of the instrument as well as the number of volts, amperes, &c., to which the readings correspond. In most cases this will necessitate two columns of figures in the note book for each set of readings, namely, one for the reading of the instrument, headed "reading," and one for the equivalent actual value, headed "true value."*

(*f*) Make a note of the instrument used for each set of measurements, so that it can be identified afterwards, if necessary. Instruments usually have a maker's number stamped upon them, which it is convenient to use for this purpose.

(*g*) Take care to avoid errors of reading in using instruments which are affected by magnetic fields, such as the fields due to currents flowing in conductors near them. Most instruments, except electrostatic voltmeters, hot-wire instruments, and some instruments of the dead-beat moving coil type, are strongly affected by any external magnetic field. They should therefore be placed at a considerable distance from any dynamo or motor, and as far as possible from conductors carrying heavy currents. The effect of a "stray" field can often be detected by the motion of the needle caused by starting and stopping the current in the conductors before the instrument is connected up. The fact that no deflection can be detected under these circumstances is not a proof that the readings of the instrument will be entirely unaffected.

---

* In the headings given later as examples of the method of entering up observations, separate columns for "reading" and "true value" have not always been given. This course has been adopted in order to keep the tables as compact as possible; a further subdivision of the columns must, therefore be made where necessary.

(*h*) Keep a "calibration curve" for each instrument. Every instrument must from time to time be compared with a standard instrument, or calibrated in some other way. A curve should then be plotted showing the *true value* corresponding to *actual readings* on the instrument. This "calibration curve" should afterwards always be used for correcting readings taken on the instrument. The calibration must be repeated at short intervals in order to avoid errors. A slight jar, the fact of being placed near a conductor carrying current, the gradual alteration in the strength of the permanent magnets and weakening of the springs of the instruments, are all sufficient to cause variation in the readings. Tachometers and speed counters must also be checked from time to time by means of a hand counter and stop watch.

(*i*) When a series of readings is to be taken, they should be taken in a regular sequence, *i.e.*, either for increasing or for decreasing values of the variable quantity. If possible, a curve showing the result of the readings should be roughly plotted as the readings are taken. This will be of service in showing at what intervals readings would be of most value, and so make it unnecessary to interpolate isolated readings afterwards, when it may be difficult to imitate exactly the previous conditions of the experiment.

(*k*) Too much reliance should never be placed upon a single reading or observation. If the observation forms one of a series, its accuracy can generally be confirmed by comparison (usually by means of a curve) with the other readings. If this is not possible, the reading should be taken several times, preferably with the conditions varied each time, so that the actual readings on the instruments do not remain the same.

(*l*) It is to be remembered that all voltmeters (except electrostatic voltmeters) take a small amount of current. In most cases the smallness of the current makes it negligible, but where the main current is small, or exceptional accuracy is required, this may be no longer permissible.†

(*m*) When readings are taken on instruments having a torsion head (*e.g.*, torsion voltmeters, Siemens dynamometers, and wattmeters, &c.), the pointer should be moved into the position of balance first from one direction and then from the opposite direction for each reading. This is a necessary precaution on account of the tendency of the swinging pointer to stick slightly to one side of the position of balance where the spring is only very slightly distorted.

(*n*) Many instruments (especially ammeters having a shunt composed of a different metal from the moving coil and electromagnetic voltmeters which have a comparatively low resistance) alter their readings slightly after being connected to the circuit for some time. This is due to the gradual warming of the windings and the consequent alteration in their resistance.

(*o*) When running a machine, do not neglect the lubrication of the bearings or the adjustment of the brushes. If the machine is provided with ring lubricators, see that the rings revolve properly and carry oil with them. If there is too much oil in the oil chamber, it will hinder the rotation of the rings. If the lubrication is by "syphon" or "sight-feed," see that the action is slow and regular. Adjust the brushes after each variation of load if there is any sign of sparking.

(*p*) When a number of readings on various instruments have to be taken at once, it is usually important that they should be taken *simultaneously*, to avoid errors caused by the fluctuation to which the quantities to be measured are liable. If several observers are taking the readings, a signal should be given, so that they may note their readings at the same moment.

---

† A Cardew hot-wire voltmeter takes about 0·3 ampere at its full reading. Other types of voltmeter usually take less than this. The current in a good dead-beat type of voltmeter is usually very small—probably about $\frac{1}{100}$ ampere.

CHAPTER II.

MEASUREMENT OF ARMATURE AND FIELD RESISTANCES.

It is important to determine the electrical resistance of the various conductors in a dynamo or motor. The usual method of resistance measurement by the Wheatstone Bridge is generally not sufficiently accurate for measuring the resistance of the armature or series magnet winding, because these resistances are so small. Four methods for measuring these small resistances are given of different degrees of sensitiveness.

Descriptions of the measurement of resistances by various forms of Wheatstone's Bridge are given in electrical text books, and need not be repeated here.

Before describing the more delicate methods of resistance measurement, the following simple method, which is often sufficiently accurate for small machines whose armature resistance is not too low* is given. The instruments required are a voltmeter (reading low voltages accurately, if used for armature resistances) and an ammeter.

Experiment I.—MEASUREMENT OF ARMATURE RESISTANCE.

Method 1.—By Voltmeter and Ammeter.

DIAGRAM OF CONNECTIONS.

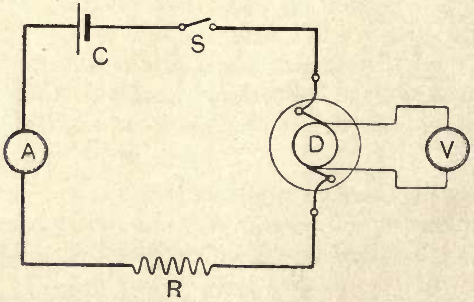

FIG. 1.—MEASUREMENT OF ARMATURE RESISTANCE.

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* See footnote page 9.

D Dynamo armature (stationary).
R Resistance.
C Source of current—either 2 or 3 secondary cells or power mains.
A Ammeter.
V Voltmeter.
S Switch.

Connections.—Connect in series with the terminals of the dynamo of which the armature resistance is to be measured, an ammeter, switch, the source of current (cells or current mains), and a resistance of a magnitude sufficient to reduce the current to a convenient value. Also connect a voltmeter to the points between which the resistance is to be measured. If the resistance of the armature winding alone is to be determined, the voltmeter leads may be connected to a pair of commutator segments under opposite magnet poles by inserting them between the brushes and commutator, allowing each wire to make contact with *one segment* only.

If the total internal resistance of the dynamo from terminal to terminal is to be measured, the voltmeter must be connected to the terminals of the machine.

Instructions.—Close the switch and take simultaneous readings on the ammeter and voltmeter, after adjusting the resistance R, to give the readings suitable values.

Repeat the readings several times with different values of the current.

The value of the armature resistance is obtained by dividing the current in the circuit by the value of the voltage at the armature terminals, since by Ohm's law

$$\text{Resistance} = \frac{\text{Voltage}}{\text{Current}}$$

The results of the measurement should be entered on a form, as shown on the following page.

MEASUREMENT OF ARMATURE RESISTANCE BY COMPARISON OF DEFLECTIONS.

General Explanation.—When two resistances have the same current flowing in them, the differences of potential existing at their terminals are proportional to the magnitude of the resistances. The potential difference is in each case numerically equal to the product of current and resistance.

MEASUREMENT OF ARMATURE RESISTANCE.

Date .... Observer ....

Dynamo No. .... Type of Armature............

Output .... volts ...... amperes at ...... revs. per min.

CURRENT.		VOLTAGE OF ARMATURE.		
Ammeter No. .... Constant		Voltmeter No. .... Constant		RESISTANCE (calculated).
Reading.	True Value.	Reading.	True Value.	

Mean value of resistance = ... measured (at commutator or between machine terminals).

Use is made of this fact to compare the unknown armature resistance with a known resistance, by comparing the deflections of a galvanometer produced by the two differences of potential.

Experiment II.—MEASUREMENT OF ARMATURE RESISTANCE.

Method 2.—By Comparison of Deflections.

DIAGRAM OF CONNECTIONS.

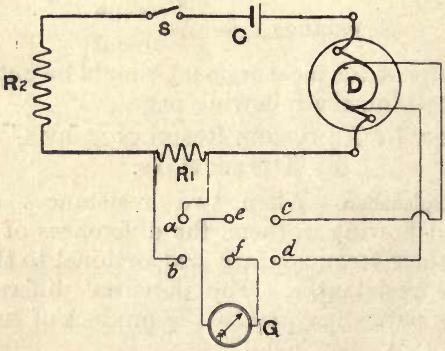


FIG. 2.—MEASUREMENT OF ARMATURE RESISTANCE.

D	Dynamo armature (stationary).
R_1	Standard low resistance approximately equal to the armature resistance.†
R_2	Adjustable resistance.
C	Cell, preferably one or two secondary cells.
G	Galvanometer.
S	Switch for breaking main circuit.
a, b, c, d, e, f	Double-pole 2-way switch, or mercury contacts.

Connections.—Join in series one or two secondary cells, an adjustable resistance, a small standard resistance, the armature to be measured, and a plug key. From the standard resistance and armature, respectively, bring pairs of leads to *a b* and *c d* on the throw-over switch, so that the galvanometer may be put in parallel with either of these resistances by connecting either pair to *e f* by the switch.§

The connections to the armature for the main current may be made to the dynamo terminals. The field winding must be disconnected. The potential wires leading to the throw-over switch may be best connected to the armature by pressing them between the brushes and the commutator. Clean the ends of the wires and the commutator segments upon which the wires press *very carefully* to ensure good contact. Count the number of commutator segments, and make sure that the wires press on opposite segments, and that each wire makes contact with one segment only.

The galvanometer may be set up at a considerable distance away, since the resistance of the leads does not affect the accuracy of the measurement, if small compared to the galvanometer resistance. The galvanometer should have a uniformly divided scale, and its reading should be proportional to the deflecting current within the limits employed. After closing the plug key, adjust the variable resistance R_2 so that the galvanometer deflection is of a suitable magnitude when the throw-over switch is in either position.

---

† This and the preceding methods are only suitable for measuring armature resistances between about ·1 and ·001 ohm. The greater the current for which the dynamo is designed, the less the armature resistance. Very small machines may have as much as 1 ohm resistance, or even more in the case of small motors. Large dynamos for high currents frequently have an armature resistance of less than $\frac{1}{10000}$ ohm. Such small resistances must be measured by some form of Thomson Bridge, as described on page 16.

§ If a suitable switch is not available, a board with four small holes corresponding to a, b, c, d may be used. The holes are filled with mercury, and the ends of the leads from the galvanometer are dipped into a and b or c and d.

If a reflecting galvanometer is used, the deflection should be between 100 and 200 small scale divisions. If the galvanometer is very sensitive, it may be necessary to "shunt" it in order to get suitable readings; the resistance of the shunt must not be low enough to materially alter the amount of current flowing through the resistances to be compared. Often a resistance in series with the galvanometer will give the required result.

Notice that in both positions of the switch the deflection is to the same side of the scale.

Instructions.—By means of the throw-over switch, connect the galvanometer to the standard resistance.

Note the deflection on the scale.

Reverse the switch, so that the galvanometer is connected to the armature.

Note the deflection.

Reverse the switch again, and repeat the first reading, in order to avoid errors due to a fall in the voltage of the battery.

The three readings should be repeated five or six times with slightly different currents obtained by altering the resistance R_2.

The armature resistance $= X = R_1 \frac{d_2}{d_1}$ when the symbols have the meaning given below.

Calculation.—

Let d_1 be the mean of the first and third readings indicating the potential drop in the standard resistance.
d_2 the second reading due to the drop in the armature.
R_1 the known resistance of the standard.
X the unknown resistance of the armature.
V_1 the fall of potential in the standard resistance when the current is flowing.
V_2 the fall of potential in the armature.

The current in the standard resistance $= \frac{V_1}{R_1}$.

In the armature the current is $\frac{V_2}{X}$.

Since it is the same current which flows in both,

$$\frac{V_1}{R_1} = \frac{V_2}{X} \text{ or } X = R_1 \frac{V_2}{V_1}$$

The deflections of the galvanometer are proportional to the differences of potential applied to its terminals.

Hence $\frac{d_2}{d_1} = \frac{V_2}{V_1}$

$X = R_1 \frac{V_2}{V_1} = R_1 \frac{d_2}{d_1}$ and X is thus determined.

When the armature becomes heated during working its resistance increases. It is frequently necessary to measure the armature resistance when hot. For this purpose the measurement may be made immediately after the machine has been working, before it has had time to cool.

If the resistance of the brushes, contacts, and leads to the dynamo terminals is to be included with the armature resistance, the potential wires must be joined to the dynamo terminals instead of being inserted between the brushes and commutator. The contact resistance between the brushes and commutator is liable to considerable variation, especially if the commutator is not *quite clean.*

Enter the particulars of the measurement thus :—

MEASUREMENT OF ARMATURE RESISTANCE.

Date.................................Observer ....
Dynamo No. ....Type of armature ......
Output.........volts........amperes at........revs. per min.
Standard low resistance R_1 = ...ohm.
Galvanometer No.............at......distance from scale.*

d_1 Reading due to resistance R_1	d_2 Reading due to armature resistance.	$R_1 \times \frac{d_2}{d_1}$ Armature resistance.	Condition of measurement.†

Mean value of armature resistance = ...

---

* The distance from scale is to be given in the case of a reflecting galvanometer, unless this distance is always the same for the galvanometer employed.

† In the last column state whether the armature was measured while hot or cold, and whether the resistance was measured between the dynamo terminals or at the commutator.

The resistance of copper increases by ·00238 of its value for every degree Fahrenheit increase in its temperature. If we measure the resistance of an armature when at atmospheric temperature, and also immediately after a continued run at full load, we can calculate the rise in temperature which has occurred.

This method is a more accurate one for finding the temperature rise, than the usual one of applying a mercury thermometer to the outside of the armature.

Potentiometer Method.—For still greater accuracy it is better to measure the armature resistance by the potentiometer method, which is the next to be described.

MEASUREMENT OF ARMATURE RESISTANCE BY THE POTENTIOMETER.

General Explanation.—When two resistances have the same current flowing in them, the difference of potential existing at the terminals of each resistance is proportional to the magnitude of that resistance. The potential difference is numerically equal to the product of the current and resistance in each case.

Use is made of this fact to compare an unknown armature resistance with a known standard resistance.

The two resistances are connected together in series with a cell. When current flows through them, the difference of potential between the ends of the two resistances is compared by means of a potentiometer.

The potentiometer consists essentially of a stretched bare wire of uniform high resistance, in which a current is made to flow from a secondary cell. Since the resistance of the wire is uniform, there will be a uniform fall of potential along the whole length of the wire, and the drop of potential between any two points on the wire will be proportional to the length of wire between these points, so long as the current is maintained constant.

In order to compare two E.M.F.'s, the length of wire is determined having a fall of potential equal to one of the E.M.F's. The length is then found in which the fall of potential is equal to the other E.M.F. The two lengths of wire bear the same ratio to each other as the two E.M.F.'s which it is desired to compare. The comparison is thus reduced to the measurement of two lengths of wire by means of a scale.

The length of the potentiometer wire in which the fall of voltage is equal to the voltage between the ends of the resistance to be compared must be determined by trial with a galvanometer.

The galvanometer is connected in series with the given source of E.M.F., and is then connected to two points on the potentiometer wire in such a way that the difference of potential between these points tends to send current through the galvanometer in the opposite direction to the given E.M.F. When the voltage of these two opposing sources is equal, the current through the galvanometer becomes zero. The length of wire between the points so found forms the basis for comparing the given E.M.F. with that of any other source which can be neutralised by the difference of potential of some other length of the potentiometer wire.

The battery supplying current to the potentiometer must always have a higher E.M.F. than any E.M.F. to be measured upon it. A simple type of potentiometer, consisting of a uniform stretched wire with movable contact and evenly divided scale, is sufficient for accurate measurements, when the resistance to be measured is not very small. The more complete forms of potentiometer by Crompton and others are more convenient for constant and varied use, and are capable of much finer adjustment.

Experiment III.—MEASUREMENT OF ARMATURE RESISTANCE.

Method 3.—By Potentiometer.

Connections.—Connect the potentiometer wire to one or two secondary cells. Connect the known resistance R_1 and the armature D in a separate circuit including a secondary cell, key and an adjustable resistance R_2. Connect the galvanometer to A, one end of the potentiometer wire, and to the sliding contact through two-way switches, or similar contrivance for connecting in series with the galvanometer the standard resistance and the armature D alternately.

The leads from these resistances must be connected to the switch in such a way that the drop of potential in both resistances tends to send a current through the galvanometer in the direction from A to P if the current in the potentiometer flows from A to B. Otherwise it will be impossible to find a point of balance on the wire, *i.e.*, *similar poles* of the secondary cells in the two circuits must be joined to A. As in the previous experiment, the two-way switch, *a*, *b*, *c*, *d*, *e*, *f* may be replaced by four mercury cups at *a*, *b*, and *c*, *d*, into which the potentiometer wires, *e*, *f*, may be alternately dipped.

DIAGRAM OF CONNECTIONS.

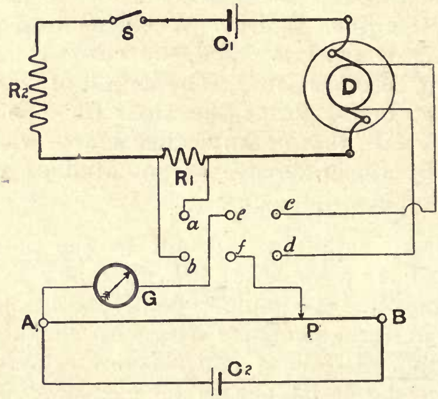


FIG. 3.—MEASUREMENT OF ARMATURE RESISTANCE.

D	Dynamo armature.
R_1	Standard low resistance.
R_2	Adjustable resistance.
C_1 C_2	Cells, preferably secondaries.
G	Galvanometer.
A B	Potentiometer wire.
P	Contact key.
S	Switch for breaking main circuit.
a, *b*, *c*, *d*, *e*, *f*,	Double-pole 2-way switch, or mercury contacts.

Instructions.—Close the keys in the main circuit and move the two-way switch so that the known resistance R_1 is included in the galvanometer circuit.

In order to make sure that the connections have been rightly made, press the contact key first at one end of the wire A B and then at the other. In one case the galvanometer should be deflected to the right, and in the other case to the left. If both deflections are to the same side, reverse either the potentiometer battery, or interchange the connections *e* and *f* on the reversing switch. By trial find the point on the wire giving no deflection, and note the number of divisions on the scale between this point and the end A of the wire.

Alter the switches so as to substitute the armature for R_1. Find the point of balance, and again note the reading on the potentiometer scale. Repeat the reading with the standard resistance, in order to avoid errors due to the running down of the batteries.

Repeat the readings with a slightly different current in the circuit containing R_1 and X, after altering R_2.

Calculation.—

Let d_1 be the mean of the first and third readings taken with the known resistance R_1.

d_2 the second reading taken with the armature in the galvanometer circuit.

X the armature resistance.

Then, by similar reasoning to that given on page 11, we have

$$X = R_1 \frac{d_2}{d_1}$$

Enter up results as shown on page 11.

The potentiometer method of measuring small resistances is more accurate than the method of galvanometer deflections previously described. The deflection method is simpler, and generally accurate enough for armatures not having a very low resistance.

The accuracy of the potentiometer measurement is due to the fact that it is a *nul* method, *i.e.*, the galvanometer is at zero when the final reading is taken. An extremely sensitive galvanometer can therefore be used. It is well to use a "shunt" with the galvanometer until the point of balance on the potentiometer wire has been roughly determined, in order to avoid injury through the currents which will flow through the galvanometer during the first trials. The final adjustment should be made with the galvanometer as sensitive as possible.

Measurement of Low Armature Resistance by Thomson Bridge.—In the case of very large armatures where the resistance is less than $\frac{1}{1000}$ ohm. it is necessary to employ still more sensitive methods of measurement.

The best-known method is that known as the Thomson Double Bridge. The principle of the measurement is as follows :—

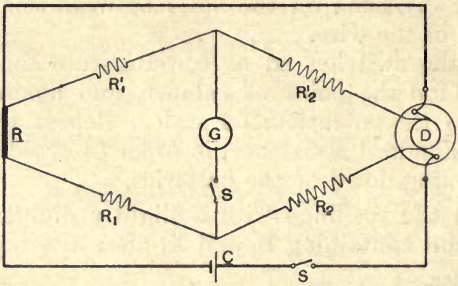


FIG. 4.—MEASUREMENT OF ARMATURE RESISTANCE BY THOMSON BRIDGE.

The connections are shown in Fig. 4, where

D is dynamo armature to be measured.

R_1 R_1' are resistances, usually of the plug resistance-box type, both capable of being varied, but preferably so arranged as to be always equal to one another.

R_2 R_2' are plug resistances also capable of variation and preferably kept equal to each other.

R is a standard low resistance (or in some forms of the bridge a uniform graduated rod with sliding contact).

G is a sensitive galvanometer.

C is a battery for sending current through R and D.

S S are keys for closing the external and galvanometer circuits.

The measurement is made by altering the values of R_1 and R_2 until no current flows through the galvanometer when the galvanometer key is closed.

As stated above, it is usual to arrange that R_1 and R_1' are kept equal, and similarly R_2 and R_2'.

It is essential that the ratio between $\frac{R_1}{R_1'}$ should always be the same as the ratio $\frac{R_2}{R_2'}$

When the condition of balance is found

$$D : R :: R_2 : R_1, \textit{ i.e.}, D = R.\frac{R_2}{R_1}$$

The method is made more sensitive by increasing the strength of the current in the circuit containing R and D.

In this method of measurement, both the resistance of the leads from the armature to the bridge, and variations of the voltage of the battery, produce no sensible effect on the readings. In a test house it is consequently usual to arrange the bridge and galvanometer at some distance away from the testing bed, and to employ long leads, so that the actual measurement may be made in a quiet and undisturbed room. In such cases a signal bell is used to give the operator warning when connections are complete on the dynamo.

The Thomson Bridge is made up in a variety of forms for special purposes, but isolated resistance boxes may be used if a complete bridge is not available.

In a newly-completed armature the resistance from segment to adjacent segment should be measured all round the commutator, and also the resistance between every pair of opposite segments. This is done less with the idea of checking the actual value of the armature resistance than in order to detect any lack of symmetry in the connections, or any faulty connection in the winding.

Measurement of the Resistance of Field Windings.—The magnet windings of dynamos and motors are of two kinds, viz.: series windings intended to carry the main current of the machine, having therefore a low resistance; and shunt windings, designed for a small current only, having a comparatively high resistance.

Series Winding.—The low resistance series winding may be measured in any of the four ways already mentioned. The method given in Experiment I. being the simplest is the most usually adopted where special accuracy is not required.

Shunt Winding.—As the resistance of a shunt field winding is always fairly large, it can be easily measured by any of the usual methods of measuring resistances, *e.g.*, with a Metre Bridge, or Post Office type of Wheatstone Bridge.

Since the shunt winding has a high self-induction, the key in the battery circuit must always be depressed *before and released after* the galvanometer key when making a measurement, or the galvanometer will receive a large induction current.

The method of resistance measurement described in Experiment I., in which a volt and ampere meter are used, is equally applicable to the shunt resistance, and this is the method more usually employed in the test house than any other.

If the current supplied to the winding for this measurement is its normal working current, or if the voltage applied at the terminals is the normal working voltage, an interesting series of values of the resistance may be obtained as the winding gradually becomes heated by the current, and its resistance increases in consequence.

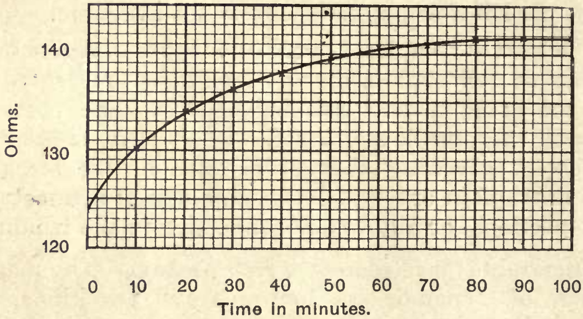


FIG. 5.—CURVE SHOWING INCREASE IN RESISTANCE OF SHUNT WINDING.

Fig. 5 gives a curve obtained in this manner. The shunt windings of a small dynamo were connected to the 100-volt mains, and readings of the current flowing through the coils were taken every 10 minutes. The voltage at the terminals of the windings was also observed, and the resistance of the windings calculated. It will be seen that the resistance increased rapidly at first, and afterwards more slowly as it approximated to its final value. After about 1½ hours the final resistance of 141·8 ohms was practically reached.

Variable Shunt Resistance.—If the exciting current of a dynamo is supplied from a constant source of potential applied at the terminals of the winding, the current (and consequently the magnetising force) will decrease in the same proportion that the resistance of the windings increases. In order to provide means for correcting such variations, it is usual to provide a resistance capable of fine adjustment in series with the shunt winding of a dynamo. This resistance is inserted in the exciting circuit when starting the dynamo cold, and is gradually cut out as the readings of the voltmeter indicate the necessity for more exciting current.

It is obvious that the range of the variable shunt resistance must be at least as great as any variation in resistance of the shunt winding caused by heating, in order that the exciting current may be kept constant by regulation of the shunt resistance. In the experiment illustrated by Fig. 5 the variation in the resistance of the shunt coils was from 123·8 ohms at starting to 141·8 ohms when the coils had become fully heated, *i.e.*, a variation of 18 ohms. A regulating resistance for the dynamo in question would consequently have to be capable of a variation of 18 ohms in order to compensate for variation of the field resistance alone.

It will be pointed out later that a further possible variation is required in order to increase the field excitation sufficiently to counteract the fall of voltage due to reactions caused by current in the armature.

Determination of Temperature by Increase of Resistance.—A careful determination of the increase in resistance of the field windings is of importance as affording the most accurate means of determining the total average rise in temperature of the coils. The resistance of a copper conductor increases by practically 0·428 per cent. of its value at the normal temperature of 15° C. for each degree Centigrade by which it is raised above that temperature.

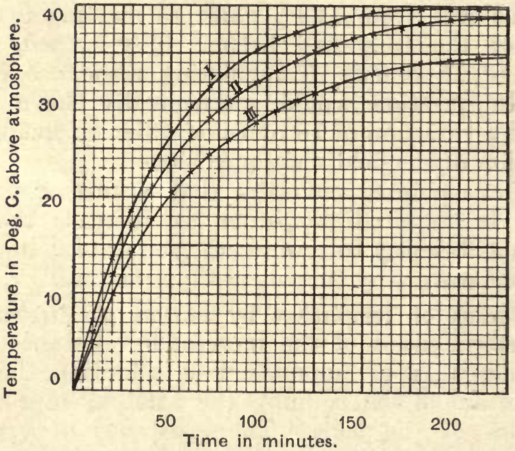
In order to find the temperature of the coils after they have become heated, by measurement of the alteration in their resistance, the following formula may be employed:—

$$t_c = \frac{r_2 - r_1}{r_1} \times \frac{100}{\cdot 428}$$

$$t_F = \frac{r_2 - r_1}{r_1} \times \frac{100}{\cdot 238}$$

where t_c = rise in temperature in degrees Centigrade.
t_F = ,, ,, ,, Fahrenheit.
r_1 = resistance when cold.
r_2 = resistance when hot.

The upper curve on Fig. 6 shows graphically the result of a determination of the temperature rise in the shunt windings of a small 2-pole motor made in this way. The lower curves on the same figure show simultaneous readings taken with mercury thermometers placed with their bulbs in contact with the windings, and well covered in with cotton wool to prevent radiation of heat as far as possible. The thermometer, whose readings are shown by the lowest curve, was placed on the outside of one of the magnet limbs. The middle curve gives the readings of a thermometer placed between the magnet limbs against the inner surface of one limb.



Curve I.—Rise in temperature calculated from resistance.
,, II.—Rise in temperature measured on thermometer between magnet limbs.
,, III.—Rise in temperature measured on thermometer outside magnet limbs.

FIG. 6.—TEMPERATURE RISE IN MAGNET WINDING.

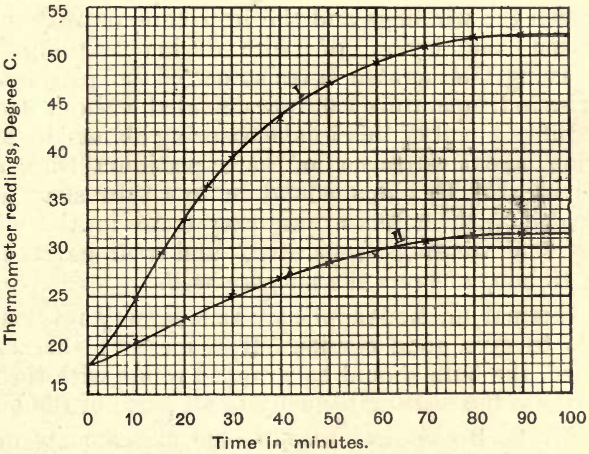
The final readings of the thermometer placed against the outside of the windings are seen to be 5°C. below the average temperature of the coils, as measured by the increase in their resistance.

If the average temperature is assumed to be the mean between the hottest and coolest layers, the hottest layer would be about 10° above the temperature indicated on a thermometer applied to the outside of the coil.

The readings here referred to were taken with the armature stationary. In revolving, the armature fans the coils and cools the outer layers, so that the temperature difference would be much greater with the machine at work.

The hottest layer is found not to be the layer next the magnet limb, since the iron of the magnet cools the layers next to it. It is usually about one-quarter of the depth of the winding from the inner layer.

In order to illustrate further the errors to which observations by means of mercury thermometers are liable, the curves on Fig. 7 are given. They indicate the readings simultaneously taken on two thermometers placed respectively between the limbs and on the outer side of one limb of a small 2-pole motor. The thermometers were placed closely against a wrapping of thin fibre with which the windings were protected. The magnets being rather close together, the inner thermometer was in a very well-protected position, and received heat from both magnet limbs. Both thermometer bulbs were covered with cotton wool, and a constant potential was applied to the magnet windings.



Curve I.—Readings of thermometer between magnet limbs.
„ II.—Readings of thermometer outside magnet limbs.

FIG. 7.—TEMPERATURE RISE IN MAGNET WINDINGS.

It will be seen that the final readings of the thermometers differed by nearly 21°C. A little carelessness in wrapping up the thermometer bulb during a test may cause a still greater error than would be incurred by taking either of the curves in Fig. 7 as giving the true temperature of the coils.

The curves sufficiently show how erroneous may be the conclusions as to the temperature of the windings, if only drawn from the readings of a thermometer placed on the outside.

It should be remembered that the actual temperature of the inner layers of the windings must be higher than the temperature indicated by any of the curves, since even the highest curve on Fig. 6 only gives the *average* temperature of all the windings.

In order to investigate the temperature of the inner layers, a spiral of fine platinum wire wound on to a flat strip of fibre or mica, and carefully covered with silk ribbon may be used. The flat strip can be inserted between the windings and the iron core, or may be laid between the layers of wire during winding. By measuring the increase in resistance of the platinum coil, its rise in temperature can be calculated without removing the coil. A coil of this kind measuring about ½in. by 3in., having about 50 turns of bare platinum wire, and a resistance of 10 ohms wound on to a thin strip of mica provided with notches like saw teeth in the edge, to keep the windings separated, and well covered with silk ribbon, answers the purpose well.

Thermal junctions applied in a similar way have also been made to give good results. If a mercury thermometer is used, the bulb should be wrapped round with tin foil to distribute the heat uniformally to all parts of the bulb.

Mr. E. Brown has made some experiments on the internal temperature of dynamo field coils*, and found that in the case of the 2-pole dynamo which he experimented upon, the temperature rise of the external layers was 29°C. the average rise through the depth of the winding was 50° C., and the maximum rise was about 60° C. Thus the maximum rise in the interior of the coil was more than double the increase which would have been registered by a thermometer applied at the surface of the coil in the usual way. There was, in fact, quite as large a difference of temperature between the hottest part of the winding and the surface of the coil as there was between the surface of the coil and the air of the room where the test was conducted. These results were obtained with the dynamo running.

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* Proceedings of the Institution of Electrical Engineers. Vol. xxx., p. 1159.

CHAPTER III.

PRODUCTION OF ELECTROMOTIVE FORCE IN A DYNAMO.

The strength of a magnetic field is expressed numerically by the pull, measured in dynes,* which would be experienced by a unit magnetic pole,† if situated in the field.

A magnetic field is usually spoken of as consisting of a number of lines of force. The density of these mathematical lines is, for convenience, so chosen that the number of lines which pass through a square centimetre of a surface which is at right angles to their direction, is also the number representing the strength of the field. Thus the number of lines of force per square centimetre gives the force which would act on a unit magnetic pole at the point considered.

Whenever an electric conductor moves in such a magnetic field so as to cut the lines of force, an electromotive force, or E.M.F., is produced‡ in the conductor. The numerical value (in C.G.S., or "absolute" units) of this electromotive force is the number of lines cut through by the conductor in 1 sec.

Thus:

$$\text{E.M.F.} = \text{Rate of cutting magnetic lines.}$$

Expressed in volts (the "practical" unit of electromotive force), the electromotive force will be the above number of units divided by 10^8 (since 1 volt is equal to 10^8 absolute units of electromotive force), so that

$$\text{E.M.F. (in volts)} = \text{Rate of cutting magnetic lines} \times 10^{-8}.$$

If the conductor moves in a direction parallel to the lines of force it cannot be said to *cut* them. In such a case no electromotive force results. If there are a number of conductors, instead of one only, in each of which is induced an electromotive force, these electromotive forces will produce a resultant electromotive force if the conductors are connected together. This will be equal to their sum, if the conductors are connected together in such a manner that the electromotive forces are all directed towards the same end of the composite conductor, which they then form.

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* A dyne is the unit of force in the absolute, or C.G.S., system of units. It is the force necessary to give unit acceleration (1 cm. per second per second) to unit mass (1 gramme). A force of one dyne is roughly equal to the weight of 1 milligramme.

† Unit magnetic pole is defined to be a pole which, if placed 1 cm. from an equal and similar pole, would be repelled with a force of 1 dyne.

‡ This electromotive force must be considered to be an experimental fact. The relation existing between the value of the electromotive force and the rate at which the conductor cuts the lines is a result of the definition given to the unit of electromotive force.

It is in this way that the total electromotive force of the armature of a dynamo is obtained.

From these considerations it follows that three factors will be sufficient to determine the voltage of a dynamo, viz. :—

(1) The number of conductors in the armature acting in series;

(2) The speed of revolution of the armature; and

(3) The number of magnetic lines cut by the conductors during each revolution.

In any dynamo, as stated above,

$$\text{Voltage} = V = \frac{\text{Rate of cutting magnetic lines.}}{10^8}$$

Now let

N = number of conductors on the circumference of the armature.

n = number of revolutions of the armature made in one minute, so that $\frac{n}{60}$ = revolutions per second.

F = number of magnetic lines which pass from the north poles of the magnet to the south poles through the armature, and are cut by the conductors.

p = number of pairs of poles of the dynamo.

Each conductor will cut through F lines twice in each revolution of the armature.

The average electromotive force induced in each conductor on the armature will be $2\frac{Fn}{60}$ C.G.S. units, since that is the average number of magnetic lines which it cuts in one second.

Between the positive and negative brushes of a dynamo there are two parallel paths formed by the conductors of the armature. Hence in a 2-pole dynamo having N armature conductors there will be two sets of $\frac{N}{2}$ conductors. In each set the conductors are connected in series, and the electromotive forces of individual conductors will therefore be added. In other words, the voltage of the armature will be obtained by adding the individual electromotive forces produced in the conductors counted from brush to brush round one half of the armature.

In a multipolar dynamo the number of conductors acting in series will be the number situated between two adjacent sets of brushes.

The number of conductors which act in series to produce the voltage of a multipolar dynamo is therefore $\frac{N}{2p}$.

Each conductor will cut through F lines twice during one revolution.

The average electromotive force induced in each conductor is thus $\frac{2.F.n.}{60}$, and the average electromotive force of the armature is $\frac{N\,n\,F}{60\,p}$ in C.G.S. units.

Hence in either case

$$\text{Voltage of dynamo} = V = \frac{N.n.F}{60 \times 10^8 \times p}\text{*} \quad \ldots \quad \ldots \quad (1)$$

In the case of a 2-pole dynamo this is equivalent to

$$V = \frac{N.n.F}{60 \times 10^8} \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad \ldots \quad (2)$$

In a dynamo already constructed, two factors only can be made to vary in the expression just given for the voltage, viz.: The speed n, and the magnetic flux F, since N and p are necessarily fixed quantities. It is therefore only by altering one of these quantities that the voltage† of a dynamo can be affected.

Also if, while either of these quantities remains constant the other is made to vary, the dynamo volts will vary in exactly the same ratio. Hence in the case of a dynamo running at constant speed, nothing will alter the total voltage of the armature except an alteration in the magnetic field. Also any increase or decrease in the magnetic flux cut by the conductors will produce an exactly proportional increase or decrease in the voltage of the machine. A similar statement would hold good for a dynamo having a constant field when subjected to variation of speed.[‡]

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* The factor p must be omitted in the case of multipolar dynamos which have only a single pair of brushes, and in which the conductors are so connected that the voltage due to the several pairs of poles is added together.

† The *total voltage* of the dynamo is, of course, here intended. The difference between the *total* and *external* volts will be discussed later.

This proportionality can be most readily shown to exist by actual experiment in the case of a dynamo whose speed is varied, while its magnetic flux is maintained constant. To carry out the experiment it is only necessary to separately excite the magnets with a constant current, to drive the dynamo armature at various speeds, and to take readings of the voltage and speed simultaneously.

Experiment IV.—DETERMINATION OF RELATION BETWEEN SPEED AND VOLTAGE OF A SEPARATELY-EXCITED DYNAMO WITHOUT LOAD.

DIAGRAM OF CONNECTIONS.

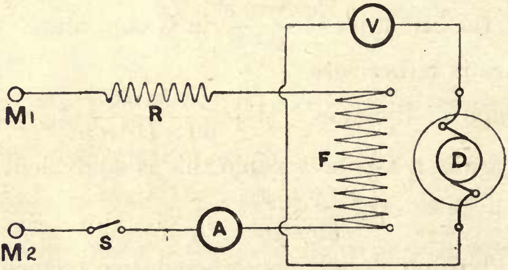

FIG. 8.

M_1 M_2	Supply mains.
D	Dynamo armature.
F	Dynamo field windings.
R	Adjustable resistance for regulating exciting current.
V	Voltmeter for measuring armature voltage.
A	Ammeter for measuring exciting current.
S	Switch for breaking field circuit.

[‡] In the case of small dynamos running at a high rate of speed, especially when the resistance of the external circuit is small, an apparent contradiction of this statement occurs. The voltage does not increase in exact proportion to the speed when the magnets are excited with a constant current. This is, however, due to an actual decrease of magnetic field owing to the eddy currents which are generated in the core of the armature, and magnetise the armature core locally in a direction opposing the main field. In well-constructed dynamos running at normal speeds, this effect should be too small to be appreciable.

Connections.—Connect the field winding of the dynamo to the source of supply. Include in this circuit an ammeter and regulating rheostat. The rheostat* should have sufficient resistance to reduce the current to the value desired, and must be capable of fine adjustment. Connect a voltmeter to the terminals of the dynamo.

Instructions.—By means of rheostat R keep the exciting current as registered by ammeter A constantly at the same value.

Note the readings of voltmeter V for various speeds of revolution of the armature. Begin with the lowest speed for which a satisfactory reading on the voltmeter can be obtained, and increase the speed by approximately equal steps for successive readings. No current is to be taken from the dynamo throughout the experiment. The readings of the speed should be taken by a hand speed-counter, or by a tachometer, or automatic speed-counter.

Any convenient method of obtaining the required variation of speed may be adopted, but the most satisfactory method is to drive the dynamo by an electric motor, and to vary the speed of the motor in the manner to be described later on in dealing with the regulation of motors.

DETERMINATION OF RELATION BETWEEN SPEED AND VOLTAGE OF A SEPARATELY-EXCITED DYNAMO.

Observer........................ Date..........................
Dynamo No...................... Type..........................
Normal Output........volts. ....amps, at........revs. per min.
Exciting Current............amps.

Armature Voltage.		Revolutions per Minute.
Voltmeter No. .... Constant		
Reading.	True Value.	

The figures in the column headed "true value" are obtained by multiplying the figures in the preceding column by the constant of the voltmeter.

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* If a suitable accumulator battery, or other constant source of potential is available, the rheostat can be dispensed with, or replaced by an ordinary constant resistance. See, however, Hint (*d*), page 2.

Throughout the experiment the brushes should remain in the same position. This should be the position giving the greatest reading on the voltmeter; its position with reference to the poles of the dynamo will depend upon the system of armature winding. In the position giving the maximum voltage at no load, the brushes have no "lead."

The foregoing table shows the method to be adopted in entering up the results.

The results should be plotted on squared paper as shown in Fig. 9, speed being plotted horizontally and voltage vertically. The curve obtained is a straight line passing through zero. This indicates that speed and voltage bear a constant ratio to each other, and that the voltage becomes zero when the speed of revolution of the armature becomes zero.

The experiment may sometimes be useful in determining the magnetic flux through the armature of a dynamo.

If the number of conductors on the armature is known, or can be counted, it is easy from this experiment to determine the number of magnetic lines passing through the armature core, when the exciting current has the value employed in the experiment.

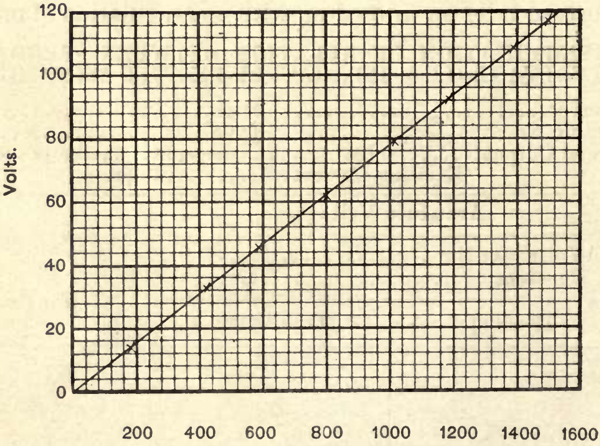


FIG. 9.—RELATION BETWEEN SPEED AND VOLTAGE OF A DYNAMO.

In the 2-pole dynamo on which the above readings were taken, the number of armature conductors was 360. At its normal speed of 1,450 revs. per minute the formula (2) p. 25.

$$V = \frac{N n F}{60 \times 10^8}$$

becomes $113 = \dfrac{360 \times 1450 \times F}{60 \times 10^8}$

whence $F = 1{,}300{,}000$ (roughly) = number of magnetic lines passing through the armature with 1·1 amperes excitation (this being the exciting current during the experiment).

The nature of the curve obtained in Experiment I. gives no further information as to the quality of the design or construction of the dynamo, since the curve in Fig. 9 must always be a straight line passing through the origin O, and could therefore be determined completely by a single observation made at any speed.

CHAPTER IV.

The Magnetic Circuit.

So far we have spoken of the magnetic field of the dynamo without considering how the field is produced, except that it is due to the action of a current circulating round the field magnets. We have now to determine what relation the magnetising current bears to the strength of the field produced.

The **magnetising force** producing the magnetic field is proportional to the product of the strength of the current circulating round the magnets, and the number of times which it flows round them. The effect on the magnets is the same whether a large current flows a few times round the magnets, or a small current flows many times round them, so long as the product of the current and number of windings is the same in each case.

The number of magnetic lines, or the strength of the magnetic field, produced by a given magnetising force, depends on the length of the magnetic lines (which are always closed curves) and the nature of the medium in which they are formed. Air is taken as the standard medium, and the relative ease with which lines of force may be produced in any other substance compared with air is called the *permeability* of that substance.

The permeability of iron, usually denoted by the symbol μ, is equal to

$$\frac{\text{No. of lines of given length produced by a given magnetising force in iron.}}{\text{No. of lines of equal length produced by the same magnetising force in air.}}$$

The permeability of iron is always much higher than that of air, which is taken as unity. As a general rule it is desired to produce the maximum strength of field from the application of a minimum magnetising force. The lines of force are therefore made as short as possible, and are produced as far as practicable in iron. The shape of the iron core in which the lines of force are produced, and which forms in a dynamo nearly a complete circuit of iron, determines the path followed by most of the lines. The path thus determined is called the *magnetic circuit* of the machine.

It is of the utmost importance to determine the exact relation between the magnetising force and the number of magnetic lines produced.

This has to be done beforehand in the design of a dynamo, and the calculated relation must be checked afterwards in the completed machine.

It is very important that students should gain experience in obtaining the relation by both methods, namely, by calculation from dimensions, and by experiment on the actual machine.

Magnetisation Curve.—The relation between the magnetising force and the field produced, for a series of values of the magnetising force, may be represented by a curve drawn on squared paper. In such a curve magnetising current or magnetising force is plotted horizontally, and the corresponding value of the magnetic field passing through the armature is plotted vertically. Such a curve when drawn for a particular machine is called the magnetisation curve of the machine. The magnetisation curve can be calculated from the drawings, or assumed dimensions, of a machine before it is constructed. Students wishing to obtain a knowledge of the design of dynamos should practice making such calculations, or, still better, they should measure up the magnetic circuits of a number of dynamos, and from sketches made from these measurements they should calculate points on the magnetisation curve. By subsequently running the machine with the excitation assumed in the calculations, the accuracy of the work can be checked, and, which is still more important, a knowledge is gained of the relative importance of the various factors in the calculation.

After a short discussion of the principles involved, an outline of the method of the predetermination of the magnetisation curve will be given, with an example. The method of experimental determination from the completed dynamo will then be described.

The magnetic circuit of a dynamo is composed partly of iron and partly of the air gap between the armature core and the pole faces. The relative lengths of these two parts of the circuit exercise a great influence on the shape of the magnetisation curve.

The magnetising force must be sufficient to send the lines through the iron, and also across the air gaps, and to overcome the magnetic resistance, or *reluctance*, of both these portions of the circuit. The important difference between the iron and air portions of the circuit is that the permeability (and, consequently, the magnetic resistance offered to the passage of the lines of force) of the air gaps is constant, and is not affected by the number of lines in the circuit. On the other hand, the permeability of iron is not a constant quantity, but depends on the density of magnetic lines induced in it.

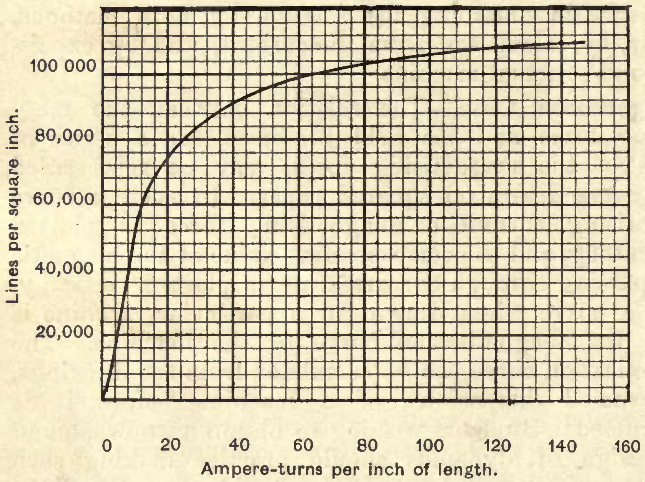


FIG. 10.—MAGNETISATION CURVE OF WROUGHT IRON.

The curve in Fig. 10 shows graphically the relation between magnetising force and number of lines per square inch produced in a sample of iron. For convenience in making use of the curve the horizontal scale is divided into "ampere-turns" instead of units of magnetomotive force. The relation between the two scales is given by the equation :

$$\text{Magneto-motive force} = \frac{4\pi}{10} \times (\text{ampere-turns}).$$

Further, the magnetising force is given in ampere-turns *per inch of length, i.e.*, the number of ampere-turns required to produce magnetic lines 1in. long. In order to produce lines of any other length, the required number of ampere-turns would be the number given by reference to the curve multiplied by the length of the lines.

The lower part of the curve is approximately straight, showing that the number of lines produced increases practically in proportion to the magnetising force.

The curve makes a decided bend to the right above the first straight portion, and beyond this bend, or "knee," the number of lines increases much more gradually compared with a given increase in magnetising force.

The iron is said to be *saturated* when subjected to a sufficient magnetising force to produce the condition represented by the curve above the bend. In general, therefore, if the iron is not saturated, the field produced in it increases rapidly with, and in proportion to, an increase in magnetising force. When the iron is saturated this proportionality ceases, and the increase of magnetic density is comparatively small for a given increase in the magnetising force applied.

The curve of Fig. 10 is the magnetisation curve for a sample of wrought iron. Similar relations between magnetising force and number of lines produced are to be found in the case of all magnetic circuits containing iron.

The important features of the curve are the initial straight portion, when the induction increases rapidly in proportion to the magnetising force, and the comparatively flat portion above the knee, where an increase in magnetising force produces only a comparatively slight effect.

The magnetisation curve for a core formed of air, or any other non-magnetic substance, would be a straight line. This would be inclined at a very small angle to the horizontal if drawn to the scale of Fig. 10, since the permeability of non-magnetic materials is very much less than that of iron.

Calculation of Magnetisation Curve.—In calculating the magnetising force for a magnetic circuit, it is advisable to take separately each portion of the circuit, and calculate the magnetising force necessary to send the magnetic lines through that portion. The total magnetising force for the circuit is obtained by adding the forces so calculated for each part of the circuit in detail.

The magnetising force producing the flux in the magnetic circuit of a dynamo is measured in terms of the *magneto-motive force.* It is directly proportional to the current flowing round the magnets, and to the number of turns of wire through which the current flows round the magnets. In actual symbols

$$\text{Magneto-motive force} = \frac{4\pi\ N.C.^*}{10} = 1{\cdot}257\ N.C$$

where N = number of turns of magnet winding
C = exciting current in amperes.

The product of the exciting current by the number of windings (*i.e.*, $N.C.$) is called the "*ampere-turns*" of the magnet windings.

The induction, or number of lines per square inch, produced by a given magneto-motive force, is equal to the magneto-motive force (M.M.F.) divided by the length of the lines in the portion of the circuit in which the magneto-motive force is taken as acting, and multiplied by the permeability of the medium in which the lines are formed.

Thus
$$B = \frac{4\pi\, N.C.}{10\ .\ L}\,\mu$$

where B = number of lines per square centimetre
L = length of lines in centimetres
μ = permeability of medium,

or, converted into British units,

$$B'' = \frac{1}{\cdot 313}\,\frac{N.C.}{L''}\,\mu$$

L'' being in inches,
and B'' in lines per square inch.

This becomes
$$N.C. = \cdot 313\,\frac{B''.L''.}{\mu}$$

In using this formula reference must be made to a table or curve giving values of μ for the particular quality of iron employed, or giving the relation between B and H, which are respectively the density of lines in iron and in air, due to a given magneto-motive force. Since $\mu = \frac{B}{H}$ μ can be calculated from the values of B and H corresponding to any value of B.

---

* The factor 4π is introduced owing to the definition of the unit of current. Also the absolute unit of current = 10 amperes, which accounts for the factor $\frac{1}{10}$.

In practice it is usually more convenient to employ curves showing the relation between ampere-turns and induction directly, as in Fig. 10. From such a curve the number of ampere-turns per inch length of lines required for a given induction may be read off directly. By simply multiplying by the length of the lines, the required ampere-turns are obtained for each portion of the circuit.

The induction, or density of magnetic lines, in any portion of the magnetic circuit is obtained by dividing the total number of lines by the section of the magnetic circuit through which they flow. The length of the lines must be estimated according to the average path which will be followed by the magnetic flux.

Example of Calculation of a Magnetisation Curve.—As an illustration of the method of calculation, assume the case of a 4-pole dynamo to give 110 volts at 700 revs. per minute, with 150 conductors on the armature.

If run at full speed without load, as in Experiment IV., the number of lines of force which must pass through the armature in order to produce the full voltage will be given by the following formula, as explained on page 25.

$$V = \frac{N\,n\,F}{60 \times 10^8 \times p}$$

V = armature voltage.

N = number of conductors on surface of armature

n = revolutions per minute of armature

p = number of pairs of poles

F = total number of lines of force.

Whence the magnetic flux through the armature

$$= F = \frac{V \times 60 \times 10^8 \times p}{N\,n} = \frac{110 \times 60 \times 10^8 \times 2}{150 \times 700} = 12{,}571{,}000$$

This is the actual number of lines necessary to give 110 volts when running on no load. The number of lines per pole will be one-half this amount.

Having determined the necessary magnetic flux, the following figures are assumed to be taken from drawings of the machine. The densities in the various portions of the magnetic circuit are obtained by dividing the sectional area of each portion by the total number of lines passing through it.

Length of path per pole in air gap............	·25in.
,, ,, ,, yoke	10in.
,, ,, ,, magnet core ...	6in.
,, ,, ,, armature core...	4in.

At 110 volts, the flux in the magnetic circuit would be sufficient to produce the following calculated densities :—

Lines per square inch in air gap = 40,000
,, ,, yoke......... = 80,000
,, ,, magnet core = 90,000
,, ,, armature core = 50,000

Referring to Fig. 10, the ampere-turns required are* :—

Ampere-turns per pole for air gap

$$= \cdot 313 \times 40{,}000 \times \cdot 25 = 3{,}130$$

,, ,, yoke $=25 \times 10 = 250$
,, ,, magnet core $=38 \times 6 = 228$
,, ,, armature core $=10 \times 4 = 40$

Total ampere-turns per pole = 3,648

This will give one point on the magnetisation curve corresponding to a voltage of 110.

By assuming a decreased magnetic flux and correspondingly decreased voltage—say, $\frac{7}{8}$ of the first value—a decreased density and altered number of ampere-turns is obtained for each portion of the magnetic circuit, and consequently a fresh value for the total ampere-turns required for the machine.

---

*If the magnetic circuit is not composed of material of the same magnetic quality throughout, a different magnetic curve should be employed for each different quality of iron used.

A succession of points calculated in this way gives the curve shown in Fig. 11.

This curve will only give an approximate general idea of the magnetisation curve of the machine. The effect of magnetic leakage is ignored in its calculation.

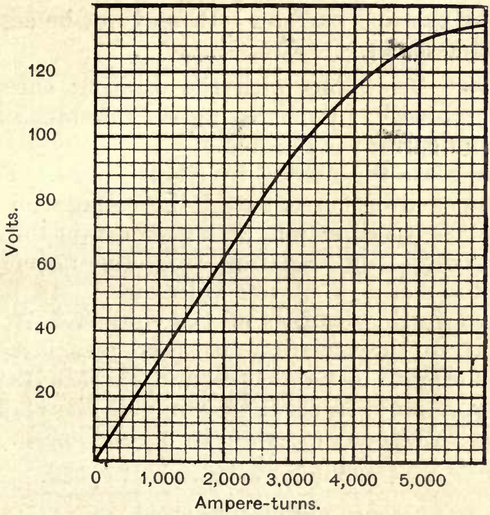


FIG. 11.—CALCULATED MAGNETISATION CURVE.

Owing to a certain proportion of the magnetic lines passing from pole to pole, or between the magnet limbs, without passing through the armature, the actual number of magnetic lines calculated for in the limbs and yoke must exceed the number required in the armature by 20 to 30 per cent. In repeating a calculation similar to the one just given this allowance should be made.

Experimental Magnetisation Curve.—The experimental method of determining the magnetisation curve of a machine is next to be described.

The machine is driven at a constant speed, while the exciting current, which is derived from a separate source, is varied for each observation.

Experiment V.—DETERMINATION OF THE MAGNETISATION CURVE, OR RELATION BETWEEN VOLTAGE AND EXCITING CURRENT OF A DYNAMO, AT NO LOAD.

Diagram of Connections.—Same as for Experiment IV., Fig. 8, page 26.

Connections.—As in Experiment IV., but the rheostat must in this case be of fairly high resistance and capable of great variation, in order to give great variation in the values of the exciting current. It need not be capable of very fine adjustment.

Instructions.—Beginning with the exciting current nil, increase it gradually by decreasing the resistance R, until the maximum current is reached.

Then decrease the current by similar steps. For each value of the exciting current read the voltage on V and the speed. The speed should be kept constant throughout the experiment. Any variation from the normal speed will affect the readings of the voltmeter. As, however, the variation in the readings of the voltmeter is strictly proportional to the variation in speed (see last experiment), it is easy to make a correction, in case the speed should vary slightly, in order to bring all the readings to their proper value corresponding to normal speed.

Let n = revs. per minute at normal speed.
n' = revs. per minute observed.
V = required voltage corresponding to normal speed.
V' = voltage actually observed at speed n'.

then $V = V' \dfrac{n}{n'}$.

In the table of results given below, the column headed "Voltage corresponding to Normal Speed" is thus obtained from the preceding column with the heading "True Value."

The readings should be entered as shown in the table, page 39.

In each case the column headed "True Value" is obtained from the preceding one by making the correction in the readings of the instrument found necessary during the calibration of the instrument. The results of

DETERMINATION OF MAGNETISATION CURVE AT NO LOAD.

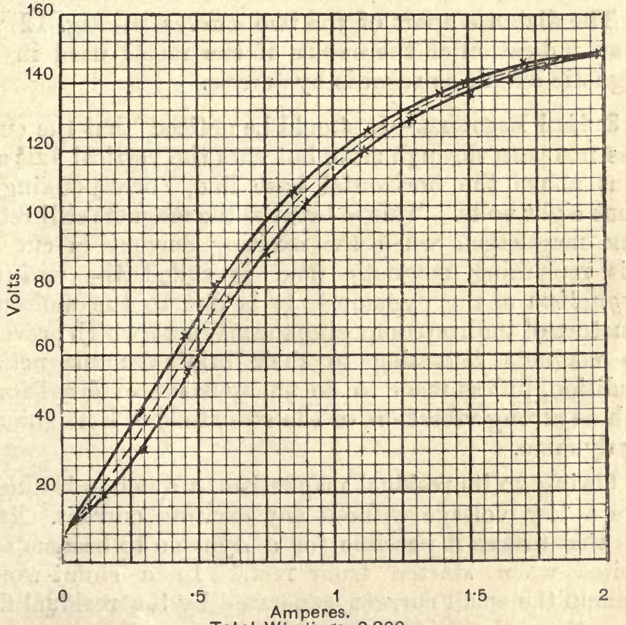
Observer.................................. Date.............................

Dynamo No. .... Type.............................

Normal Output........volts...........amps., at........revs. per min

Exciting Current.			Armature Voltage.		
Ammeter No. ..... Constant..........		Revolutions per Minute = n′	Voltmeter No. .... Constant		
Reading.	True Value.		Reading.	True Value = V′	Voltage corresponding to Normal Speed = V.

the experiment should be set out on a curve, the current being measured horizontally and the voltage of the armature vertically.



Total Windings, 2,800.

FIG. 12.—MAGNETISATION CURVE AT NO LOAD.

Fig. 12 shows the results obtained in an experiment made upon a 2-pole 3½-h.p. Crompton dynamo.

The results obtained by the experiment form two curves, one slightly above the other. The lower curve represents the values of the voltage obtained in the first part of the experiment as the exciting current was increased, and the upper curve represents the values during the process of decreasing the current.

The dotted curve is the mean curve derived from the two sets of observed readings.

Hysteresis.—The failure of the two curves to coincide is due to the *hysteresis* of the magnetic circuit. Hysteresis is a property of iron and steel which causes them to resist any change of magnetic condition. It is due to some kind of molecular friction, tending to maintain the particles of the metal in their positions of magnetisation or demagnetisation, when these positions are once assumed.

Soft wrought iron shows very little hysteresis effect, whereas steel (especially hard qualities of steel) shows the effect strongly.

The distance apart of the two curves in Fig. 12 will be an indication of the nature of the metal used in the magnetic circuit as regards hysteresis.

Residual Magnetism.—It should be noticed that the curve does not pass through zero, but cuts the vertical axis at a point above the horizontal base line, corresponding to about eight volts. This is because the magnets still retain some magnetism when the exciting current is cut off. This remaining magnetic field is called the *residual magnetism* of the dynamo. It is due to the molecular structure of the iron composing the magnets, which prevents the magnets returning to their original unmagnetised condition, unless made to do so by some external force, such as strong vibration, or the stray field of a neighbouring dynamo.

Owing to its residual magnetism, a dynamo is able to give a low voltage without any exciting current. It is this that makes it possible for a dynamo to become self-excited when started from rest. In a shunt-wound dynamo the small current generated by the residual field strengthens the field, and enables the dynamo to generate

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a stronger current, which again reinforces the action of the machine.

The height above the horizontal axis of the point of intersection of the magnetisation curve with the vertical axis is a measure of the amount of residual magnetism. For a given material the residual magnetism will depend upon the perfection of the magnetic circuit, and will be greater the more perfect that circuit is. A magnetic circuit consisting of a complete ring of iron would not tend to become demagnetised at all, since there would be no free poles.

Nature of the Magnetisation Curve.—Since in this experiment the armature revolves at a constant speed, its voltage is directly proportional to the number of magnetic lines of force which are cut by the conductors. The curve therefore represents the relation between the exciting current and the magnetic lines passing through the armature. The general form of the curve is therefore similar to the well-known magnetic curve of iron. (See Fig. 10, page 32.)

In order to compare directly Strength of Field (as measured by lines of force) and Exciting Current, it would be necessary to construct a fresh vertical scale for the curve, plotting "number of lines" instead of "volts." This may be done as explained on page 29. In ordinary practice such a curve would be of less use than the curve shown in Fig. 12, which is the curve usually designated as the "magnetisation curve."

Since the magneto-motive force is proportional to the ampere-turns, it is sometimes convenient to graduate the horizontal scale of the curve in "ampere-turns" instead of "amperes," and thus to get a more direct comparison between the magnetising force and the voltage produced.

For example, in the magnetisation curve given on Fig. 12 each small division of the horizontal scale corresponds to ·05 amp. The field windings of the machine have 2,800 turns. Hence each division would correspond to $2{,}800 \times {\cdot}05 = 140$ ampere-turns, and the horizontal scale might be figured accordingly, each of the thicker divisions being 700 amp. turns. The horizontal scale of Fig. 11, page 37, is graduated in this way.

In the same way the horizontal scale might be made to represent magneto-motive force (M.M.F.), since

$$\text{magneto-motive force} = \frac{4 \pi N C}{10}$$

where N = number of windings ; C = exciting current.

This method of division is carried out in Fig. 13.

Again, referring to Fig. 12, the curve bends over at the upper end owing to the decrease in the permeability* of the iron, and the increased magnetic leakage at higher degrees of saturation.

The magnetic leakage, which increases at higher magnetic densities, may be taken as proportional to the exciting current. It is caused by lines passing between points at different magnetic potential through the air, instead of round the iron magnetic circuit of the dynamo. The difference of magnetic potential between these points will increase with increased magneto-motive force in the circuit, *i.e.*, with the exciting current. Hence, since the reluctance of the air path is constant, the leakage will be nearly proportional to the exciting current, in fact a definite fraction of the exciting current may be looked upon as spent in producing leakage lines. From this it follows that the less the permeability of the iron becomes, the greater becomes the leakage field, due to a given magnetising force.

The "co-efficient of magnetic leakage" of a dynamo is the ratio of the total number of magnetic lines formed in the magnetic circuit to the number which actually pass through the armature, and are cut by the armature conductors.

The letter v is the usual symbol used for denoting the co-efficient of magnetic leakage. The value of v is usually between 1·2 and 1·5. Thus the total number of ampere-turns required for a dynamo in order that it may give a desired voltage is the number necessary to produce v times as many magnetic lines as would be necessary if there were no leakage.

The value of v will not vary much with the exciting current within narrow limits, since for small variations, both the useful and leakage fluxes will increase nearly in proportion to the excitation.

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* The *permeability* of iron is the ratio of the number of lines of force which a given magneto-motive force (or a given number of ampere-turns) will produce in an iron core to the number of lines which the same force would produce in a non-magnetic core, *e.g.*, in air.

The first part of the curve in Fig. 12 is approximately straight, and the tangent of the angle which it makes with the horizontal will be inversely proportional to the magnetic resistance or "reluctance" of the circuit. The steeper the inclination of the straight portion of the curve the less is the reluctance of the magnetic circuit.

In the magnetic circuit of a dynamo, some of the magnetising force will be required to send the lines through the iron of the circuit, and some will be employed in forcing them across the air gaps. Upon the relative magnetic resistance of these two portions of the circuit will depend the shape of the curve to a large extent.

The lowest part of the curve is straight, since the permeability of both the iron and the air gaps is fairly constant at low inductions, and the number of lines increase, therefore, in the same proportion as the magnetising force. The slope is determined by the ratio between the magnetic flux produced and the magnetising force.

Influence of Air Gap.—Since the permeability of iron at low magnetic densities is very great, several thousand times that of air, the magnetic resistance of the iron circuit will usually be very much less than that of the air gaps, although the air gaps form a very small fraction of the total length of the magnetic circuit. The curve will, therefore, be at first almost the same as if the air gaps had been the only portion of the circuit offering resistance to the magnetising force. It is, consequently, the reluctance of the air gaps which determines almost entirely the initial slope of the curve. This is important, since this part of the curve supplies the means of calculating the reluctance of the air gap.

In order to illustrate this, Fig. 13† is given, in which three magnetisation curves are shown, all taken from the same machine but with different air gaps. The machine employed in taking these curves was provided with moveable pole-pieces, which could be fixed at different distances from the armature, thus allowing the air gap to be varied.

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† The curves were kindly supplied by Mr. G. D. Aspinall Parr, of the Yorkshire College, Leeds.

The particulars of the clearance are stated below the curves.

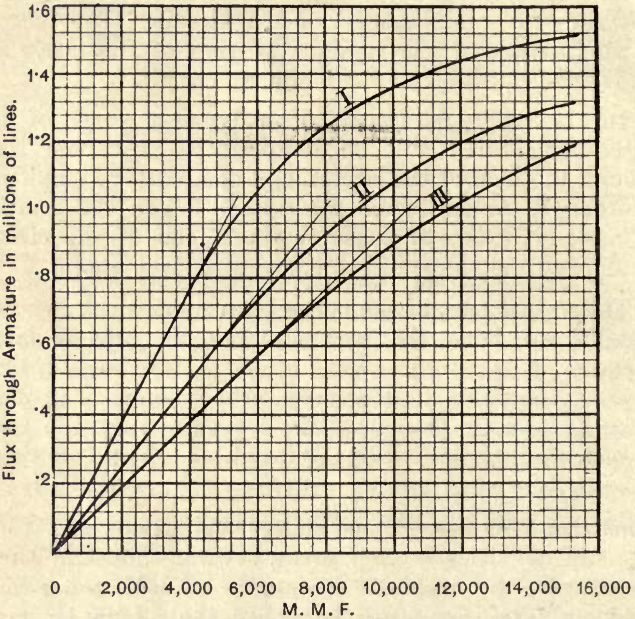

FIG. 13.—MAGNETISATION CURVE OF DYNAMO WITH VARYING AIR GAP.

Curve I. Air Gap 0·5″
,, II. ,, 0·75″
,, III. ,, 0·97″

As explained more fully on page 34, the number of lines in a magnetic circuit is equal to the quotient obtained by dividing the magnetising force by the reluctance of the circuit.

$$\text{No. of magnetic lines} = \frac{\text{Magneto-motive force}^{\ddagger}}{\text{Reluctance of circuit,}}$$

$$\therefore \text{ Reluctance of circuit} = \frac{\text{Magneto-motive force}}{\text{No. of magnetic lines.}}$$

In order to calculate the approximate reluctance of the air gap, the value of this fraction, $\frac{\text{Magneto-motive force}}{\text{No. of lines}}$

---

‡ This is an analogous law to Ohm's law of the electric circuit, where

$$\text{current} = \frac{\text{Electro-motive force}}{\text{Resistance of circuit.}}$$

must be calculated for any convenient point on the straight portion of the curve.

For convenience in calculation, in Fig. 13 the straight portion of each curve is continued up to the horizontal line corresponding to 1,000,000 lines.

In the case of the Curve I., the magneto-motive force corresponding to 1,000,000 lines is 5,200, and, consequently,

$$\text{Reluctance} = \frac{5{,}200}{1{,}000{,}000} = \cdot 0052$$

From Curve II.

$$\text{Reluctance} = \frac{7{,}900}{1{,}000{,}000} = \cdot 0079$$

From Curve III.

$$\text{Reluctance} = \frac{10{,}400}{1{,}000{,}000} = \cdot 0104$$

It will be seen that the values of the reluctance are nearly in the same proportion as the lengths of the air gap.

These calculated values are only approximate, since the calculation neglects entirely the reluctance of the iron part of the circuit. The degree of approximation is, however, sufficient to make the results of use in designing. With slotted armature cores and very small air gap the error in such a calculation is considerably increased.

Comparing Fig. 10 (page 32 ante), which represents what is practically the magnetisation curve for a magnetic circuit without air gap, with the lowest curve on Fig. 12 (page 39 ante), which is the curve for a circuit with a wide air gap, or comparing the upper and lower curves on Fig. 13 (page 42 ante) together, it is easy to see the general effect of the air gap on the shape of the magnetisation curve. The greater the influence of the air gap the more does the curve approximate to a straight line with no decided bend, and the more does it incline to the right showing an increased reluctance.

The bend divides the curve into two portions. In the lower part the permeability of the circuit is high, and the field strength increases rapidly with increased excitation, and in nearly the same ratio. The upper part of the curve above the bend corresponds to a saturated field in which slight alterations in excitation produce very little effect, so that the voltage is fairly stable.

Machines which are required to work entirely on the steep straight portion of the curve, or on the flat part above the bend, should have as small an air gap as possible.

The fact that different portions of the magnetic circuit become saturated successively causes the bend in the curve to be less well marked in many dynamos.

Determination of Number of Ampere-turns from Curve.—The magnetisation curve may be used in order to determine the number of ampere-turns which would be most suitable for a given dynamo. For an ordinary shunt dynamo the most *economical* number of ampere-turns would be the number corresponding to the "knee" of the curve, that is, where the curve begins to bend decidedly to the right, say the point opposite to 1·0 or 1·2 amperes in Fig. 12, page 39.

If the normal exciting current is considerably above or below the value thus determined, the design is not the most economical, in one case of exciting current, in the other case of material. Usually the saturation would be chosen somewhat higher, in the region where the variation of volts for a given variation of exciting current is less, to ensure steadier running.

If Experiment V. above described is being carried out on a new dynamo in order to determine the best excitation, the number of windings on the magnets will probably be known. The product of this number by the measured current will give the number of ampere-turns required.

If the number of windings is not known, the graduation of the horizontal scale in terms of ampere-turns instead of amperes may be accomplished as follows:—

Wrap round one magnet limb a few turns of stout cable in series with which is connected an ammeter. Run the dynamo at normal speed, and connect the brushes to the voltmeter as in Experiment V. Send a current through the cable from an independent source, leaving the magnet winding without current. Adjust the current in the temporary winding so as to bring the voltage of the dynamo up to the value corresponding to some convenient point on the magnetisation curve. By counting the number of turns of cable employed, and noting the current, the number of "ampere-turns" corresponding to this point can be calculated, and the number of turns in the field windings of the machine deduced from the original value of the exciting current, since the ampere-turns are the same, for the same voltage.

Often the number of windings on a bobbin may be pretty accurately estimated by determining the total resistance of the winding, and also measuring the size of the wire with a micrometer gauge. By reference to a table of wires, the resistance per yard may be ascertained for a wire of the diameter thus determined. Consequently, the length of wire on the bobbin may be calculated from the measured resistance. By measurement of the apparent *mean* length of a single winding on the bobbin the number of windings can be approximated to. By counting the number of turns in each layer, and judging from the resistance the number of layers, the exact number of turns may be arrived at in a regularly-wound bobbin.

Magnetic Density.—The question as to the most advantageous magnetic density to use in the magnetic circuit, *i.e.*, at what part of the magnetisation curve the machine should normally work, is one involving many considerations. Here, only a few main principles can be referred to.

If at the normal voltage the exciting current is such that the dynamo works upon the steep straight portion of the curve, any alteration in the excitation will produce a variation in the voltage of the machine, which will be practically proportional to the alteration in exciting current. In some machines this is required. For instance, series-excited boosters, which are discussed later on, are required to give an increase of voltage, proportional to the current in the field windings since the loss of voltage in the feeders which they have to compensate for is also proportional to the same current.

If, on the contrary, it is important that slight variations in exciting current shall produce as small a fluctuation in the voltage as possible, the field should be designed so that the machine works on the flatter portion of the curve above the bend. The change in flux of lines is then only slight for a small variation in exciting current.

The most economical design is that in which the part of the curve just above the bend is worked to. At this point the permeability of the iron is still high, so that the magneto-motive force produces a proportionately great flux of lines, while, on the other hand, the section of iron in the circuit is not greater than necessary to provide for the required number of lines without materially diminishing the permeability.

At this point the advantage of being on the less steep part of the curve is felt, while the magnets have not become fully saturated.

In some cases, as will be more fully explained later, it is an advantage to have the *pole tips* highly saturated, so that a slight variation in the magneto-motive force acting upon them may not sensibly alter the flux through them. This would, however, affect the magnetisation curve of the machine very slightly.

Power Spent in Excitation.—The power spent in excitation is generally between 1 and 2 per cent. of the maximum output of the dynamo for fairly large machines. In small machines the proportion is sometimes rather more than this.

Increasing the Voltage of a Dynamo.—The curve of Fig. 12 may be used to give directly the additional ampere-turns required in order to correct a dynamo giving too low a voltage. Thus suppose the machine is found to give 120 volts with normal excitation, whereas 130 volts are required. From the curve it is seen that the excitation at 120 volts is 1·07 amperes, and at 130 volts it is 1·25 amperes. The required increase is consequently seen to be $(1{\cdot}25 - 1{\cdot}07)\ 2{,}800 = 504$ ampere-turns, in the case assumed.

In a shunt-wound dynamo, or a dynamo excited from a constant source of voltage, the addition of windings of the same sized wire as that already on the magnets will not affect the voltage, since the additional windings increase the resistance of the coil in the same proportion as the number of turns is increased.* The current is consequently reduced as the turns increase, and *ampere-turns* remain the same as before, Consequently, if turns are added, they must be of *larger wire* than the existing winding.

---

* This will in most cases not be accurately true, since, when the windings are added *outside* the existing layers, they are of greater length, and consequently of greater average resistance. The ampere-turns are thus actually *decreased* by the added windings.

In any case it must be remembered that the addition of turns in series with the original windings reduces the current in the whole coil, owing to the added resistance through which the current flows. In most cases it will, therefore, be advisable to unwind a certain number of layers and to rewind the magnet with more turns of thicker wire giving the same total resistance, and consequently the same exciting current as before.

Fig. 12 only gives the ratio between voltage and ampere-turns at no-load. The full-load magnetisation curve determined in Experiment VIII. must be used to find the number of ampere-turns necessary to increase the voltage of a dynamo by a given amount when under load.

CHAPTER V.

ARMATURE REACTIONS.

In all the experiments and calculations previously described, the dynamo has been considered as not giving current. The strength of the magnetic field and the voltage of the armature were considered under the simplest possible conditions, in order that a clear idea might be formed of their relation to each other.

When the armature of the dynamo has a current flowing in it, another factor is introduced, affecting both the strength of field and voltage of the machine.

In order to study these effects of the armature current, experiments must be made under such conditions that they can be separated from effects due to other causes.

The relations existing between voltage and exciting current of a dynamo when not giving current have been determined. By making measurements similar to those already described, and with only the additional condition of a current in the armature, the effect produced by this current can be seen.

In all cases, the current in the armature will be found to produce a fall of voltage. In order to point out the significance of the experiments to be described, it will be necessary first to explain briefly the twofold action of the armature current in producing a fall in voltage. The first cause is electrical, the second magnetic.

Armature Ohmic Drop.—Owing to the resistance of the armature conductors, brushes, and surface contacts on the commutator, a certain amount of power, depending on the current, will be wasted in heating the parts where these resistances occur, and a certain amount of voltage will be lost in overcoming these resistances.

The drop in voltage caused by these resistances may be called the *ohmic drop*. It will be numerically equal to the product of the current, measured in amperes, multiplied by the resistance, measured in ohms, through which the current flows—that is

Loss of voltage = (resistance between dynamo terminals) × (armature current).

This "armature drop," occurring in a dynamo at various loads, may be shown graphically by a straight line drawn on squared paper, the horizontal scale of which represents the load in amperes, the vertical scale representing volts drop. It is thus represented by the straight line A C in Fig. 14.

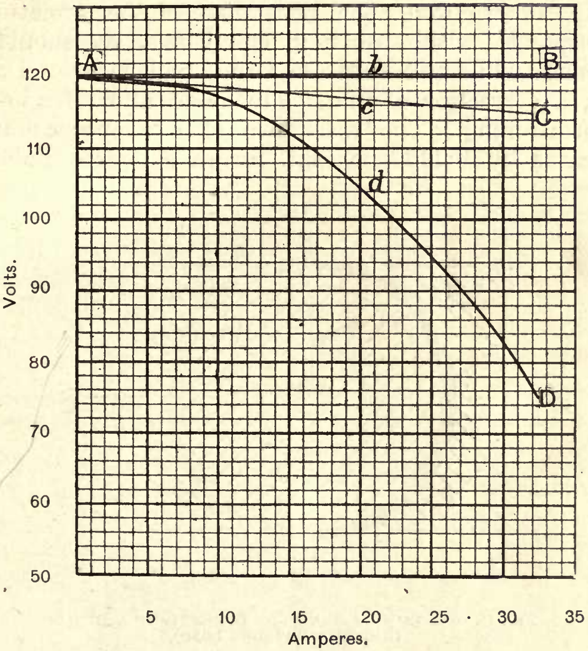

FIG. 14.—CHARACTERISTIC OF SEPARATELY-EXCITED DYNAMO.

In order to draw this line, calculate the drop for one value of the current, as just described. On the ordinate corresponding to this current, measure downwards, from the horizontal line AB, drawn to indicate the voltage at no load, a length to represent the volts thus calculated. Draw a straight line through A and the point just found.

The machine to which Fig. 14 applies has an armature resistance of ·18 ohm when hot. When giving its full load current of 20 amperes the armature drop is therefore

20 × ·18 volts = 3·6 volts. The line A C has consequently been drawn through the point c, situated in the ordinate, corresponding to 20 amperes and 3·6 volts below the maximum voltage of 120·5, the length *b c* corresponding to 3·6 volts. The line A C will then give the armature drop corresponding to any current. The drop in volts is represented by the vertical distance between the lines A B, A C on the ordinate corresponding to the current for which the drop is required.

In determining the resistance of the armature to correspond with working conditions, it should be measured while still hot from a run, or if measured when cold, a correction should be made to allow for heating when running. The resistance of a copper conductor increases by 0·238 per cent. for each degree Fah. rise in temperature. The resistance of an armature when heated to a temperature of 70° Fah. above the temperature of the atmosphere, which is the usual maximum rise in temperature allowed, will be 16·7 per cent. greater than its resistance measured when cold.

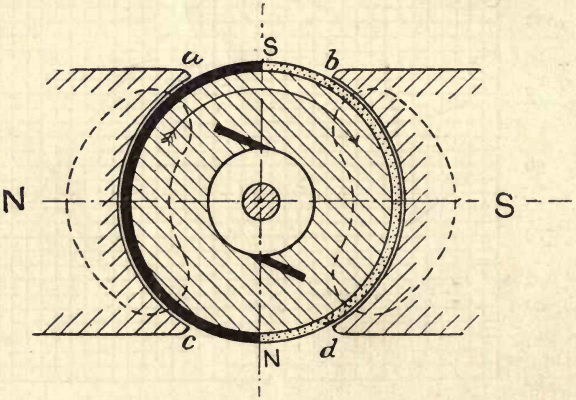

FIG. 15.—DIAGRAM OF ARMATURE CURRENTS IN A DYNAMO (BRUSHES WITHOUT LEAD).

Magnetic Reactions.—One effect of currents flowing in the conductors wound upon the iron core of the armature will be to magnetise the core. The armature itself will therefore produce a magnetic field which will influence the magnetic field due to the field-magnets.

Let Fig. 15 represent the armature rotating in the magnetic field in a direction shown by the arrow. The magnetic lines of the main field in this instance are horizontal, and are directed from the N. pole to the S. pole of the dynamo—*i.e.*, from left to right in the figure.

First, suppose that the brushes are situated symmetrically between the poles, as shown.* Then the current in all conductors to the left of a vertical diameter will be flowing in a direction away from the reader, while the current in the conductors on the right of the armature will flow towards him. The magnetic action of the armature as a whole will not be affected by the current in the end connections, and consequently the manner of joining together the ends of the conductors need not be considered. From a magnetic point of view the armature conductors will be equivalent to a conducting shell of the same general shape as the surface of the armature, carrying currents in a direction parallel to the armature shaft. The armature currents may then be replaced by a horizontally flowing current uniformly distributed over this shell. This equivalent shell is indicated in Fig. 15. The portion shown in black is that in which the current flows away from the reader, while in the portion indicated by fine dots, the current flows towards him.

The effect of the horizontal band of current thus formed will be to produce magnetic lines of force traversing the armature core in a vertical direction—*i.e.*, downwards in Fig. 15—producing a north pole at the bottom of the armature, and a south pole at the top. Hence, the general effect of the current in the armature conductors is to produce a magnetic field at right angles to the field due to the electro-magnets. The strength of this field will be proportional to the magnetising force—*i.e.*, to the ampere-turns, producing it—and inversely proportional to the reluctance, or magnetic resistance of the path along which the lines flow. The general form of the mean path followed by this cross flux is indicated in the figure by a dotted line. From this it will be seen that the lines cross the air gap surrounding the armature core twice. The reluctance of the path followed by the lines, and consequently the number of the lines, will depend largely on the width of the air gap. The length and shape of the pole tips will also greatly influence the path reluctance.

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* For simplicity in the following discussion it is assumed that the armature conductors are connected to the commutator segments immediately under them. With the usually adopted winding, corresponding conductors and segments would be at right angles to each other. The actual position of the brushes would then be at right angles to that shown in the diagrams.

The field due to the armature current is stationary, although the conductors rotate. The conductors will therefore cut the lines of force twice on each side of the armature—namely, as the lines enter and leave the core. Consequently the sum of the electromotive forces induced in the conductors by the cross-field will be zero. Also, with the brushes in the middle position, as in the case under consideration, the armature cross field will have no direct effect in strengthening or weakening the main field, since it is at right angles to it. The effect of cross magnetisation due to the armature currents upon the dynamo voltage should, therefore, be nil, apart from secondary considerations to be presently alluded to. The two magnetic fields perpendicular to each other may be considered as combined to form a single resultant field in an oblique direction. The angle of inclination of the resultant field would be given by applying the law of the parallelogram of forces. The stronger the cross field relative to the main field, the greater will be the angle of inclination of the resultant field with the direction of the main field. The effect of this distortion of the magnetic field is to strengthen the field in the neighbourhood of the leading pole tips *a*, *d*, and to weaken it near the trailing pole tips *b*, *c*. The "leading" pole tip is the most advanced point of the magnet pole in the direction of rotation, and is consequently the point at which the conductors leave the polar field, while they enter at the "trailing" tip.

Lead of Brushes.—On account of the change in the direction of the resultant field, the "neutral point"—*i.e.*, the point at which conductors on the armature move parallel to, and consequently do not cut lines of force—will be moved from the central position through an angle equal to the angle which the resultant magnetic field makes with the original direction of the undistorted field. For reasons to be explained later, the position of the brushes giving sparkless commutation is always slightly in advance of the neutral point when current flows in the armature.

The brushes are shown moved forward in Fig. 16 into the position for sparkless running.

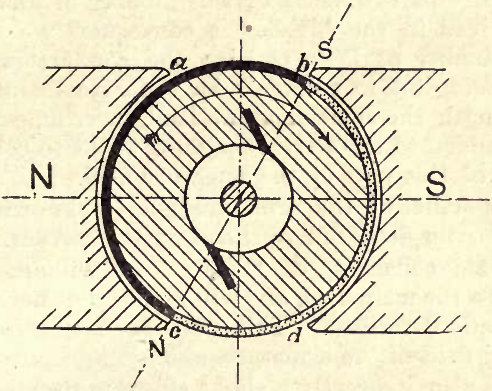

FIG. 16.—DIAGRAM OF ARMATURE CURRENTS IN A DYNAMO (BRUSHES WITH LEAD).

Since in the armature the currents in the conductors are always so directed as to flow from one brush to the other, an alteration in the position of the brushes will alter the current distribution in the armature.

The axis dividing the conductors carrying oppositely directed currents will be moved round with the brushes in the direction of rotation of the armature. Thus with the brushes will also move the axis of the cross magnetising field, which will cease to be perpendicular to that of the main field. The axis of the magnetic field due to the armature currents will always be the line joining the brushes.

Resolving the armature reaction field into its horizontal and vertical components, the horizontal component*

$$F_H = F \sin \theta$$

the vertical component

$$F_V = F \cos \theta.$$

where F = total flux of lines due to the armature current, and θ = angle between the axis of the brushes and the vertical axis of the armature.

---

* The horizontal and vertical components may be obtained graphically as the horizontal and vertical sides of a rectangle of which the diagonal represents the strength of the field.

The field consisting of $F \sin\theta$ lines of force will therefore act in a direction parallel to the main field due to the electro-magnets. The polarity of the lines will be opposite to those of the main field; the main field will consequently be weakened by this number of lines. One effect of lead in the brushes is consequently a decrease in the number of lines cut by the conductors, and a corresponding fall in voltage. In order to maintain the field strength the same as at no load, more ampere-turns must be added to the electro-magnets so as to counteract the effect of this part of the armature field.

This portion of the armature field is known as the *demagnetising field*, due to the armature current.

The field consisting of $F \cos\theta$ lines will act perpendicularly to the main field, and will distort, but not weaken, it, as already described. This portion is known as the *distorting field* of the armature.

It has also indirectly a slight effect in decreasing the strength of field, since it increases the density of lines at the leading pole tips, thereby decreasing the permeability of the iron through which these lines pass.

Having discussed the armature reactions from a general point of view, it is now necessary to enter rather more into detail.

Sparkless Commutation.—In order to prevent sparking at the commutator as the brushes pass from segment to segment, it is necessary to move the brushes round slightly in the direction of the armature rotation. The conductors connected to the segments which are momentarily short-circuited by the brushes are thus short-circuited while cutting lines issuing from the trailing pole tip of the next magnet, and sufficient reverse E.M.F. is thereby induced in them to stop the tendency to spark. The brushes are not, therefore, situated on the "neutral" axis, and a certain amount of voltage is lost in consequence.

The axis of the brushes therefore approaches the line $b\ c$, joining the pole tips as indicated in Fig. 16. Usually the brushes will not be moved quite so far forward, unless the field is unduly weakened, since the lines forming the magnetic "fringe" projecting some little way from the pole tip should be sufficient to furnish the "reversal field."

Referring to Fig. 16, the conductors between *a* and *b* and *c* and *d* may be considered as uniting to form a horizontal *demagnetising* field. The conductors between *a* and *c* and *d* and *b* will form a vertical *distorting* field.

The demagnetising field will be produced by the ampere-turns obtained by multiplying the number of conductors situated between *a* and *b* or *c* and *d* by the current flowing in them.

Let C = current given out by the dynamo.

then $\frac{C}{2}$ = current in each conductor.*

let f = distance between pole tips.

d = diameter of cylindrical space between pole faces.

N = total number of armature conductors.

Then number of conductors between *a* and *b* $= \frac{N.f}{\pi d}$

$$\therefore \text{Demagnetising ampere-turns} = \frac{CNf}{2\pi d}$$

if the axis of commutation is taken to be under the pole tips.

Thus the magnetising force producing the main field will be weakened by this number of ampere-turns. The resultant field in which the armature rotates is consequently produced by the ampere-turns on the magnets minus the demagnetising ampere-turns of the armature.

Whenever the armature carries current, the field strength and voltage will be affected approximately to the extent given by the above formula.

The importance of the cross magnetising field due to the current in the conductor between *a* and *c*, and *b* and *d* is that the distortion of the main field produced tends to weaken the field at the trailing pole tips where commutation occurs. If the field is weakened too much, sparkless commutation becomes impossible. For this reason, the ampere-turns producing the cross field must always be less than those forming the main field.

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* In a multipolar of the usual type the current in each conductor is $\frac{C}{2p}$ where p = number of pairs of poles.

In a series connected armature it is $\frac{C}{2}$, whatever be the number of poles.

Characteristic of a Separately Excited Dynamo.—The following experiment has for its object the determination of the loss of voltage produced by the ohmic drop and magnetic reaction produced in the armature by the current discussed above.

The magnets are excited by a constant current derived from a separate source. The machine is driven at a constant speed. The only factor which is varied is the armature current. The experiment consists in measuring the effect of this variation upon the voltage at the terminals of the dynamo.

Experiment VI.—DETERMINATION OF THE CHARACTERISTIC OF A SEPARATELY EXCITED DYNAMO, OR RELATION BETWEEN VOLTAGE AND CURRENT OF A SEPARATELY EXCITED DYNAMO.

DIAGRAM OF CONNECTIONS.

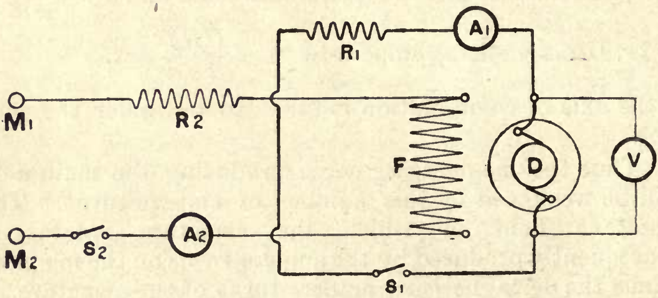

FIG. 17.

M_1 M_2	Supply mains.
D	Dynamo armature
F	Dynamo field windings.
R_1	Adjustable resistance for varying the load.
R_2	Adjustable resistance for regulating exciting current.
A_1	Ammeter for measuring load current.
A_2	Ammeter for measuring exciting current.
V	Voltmeter for measuring dynamo voltage.
S_1	Switch for breaking load circuit.
S_2	Switch for breaking field circuit.

Connections.—Join the field of the dynamo to a source of current through a regulating resistance, ammeter, and switch. Connect the dynamo terminals to a variable resistance suitable for giving a variation of current up to its value at full load. In this circuit also include an ammeter and a switch. Connect the dynamo terminals also to a voltmeter.

Instructions.—Throughout the experiment keep the exciting current, as read on ammeter A_2, constant by altering R_2 when necessary. Before closing the switch S_1 in the main circuit, read the volts of the dynamo on V. Then close S_1, and give the resistance R_1 first its maximum value. Afterwards, by successive steps, decrease the resistance of R_1 until the dynamo gives its maximum current. For each value of R_1 read the dynamo current on A_1 and the volts on V. After each change in the current, notice whether the brushes show any sign of sparking. If so, move them round into the position where the sparking is least.

DETERMINATION OF THE CHARACTERISTIC OF A SEPARATELY EXCITED DYNAMO.

Observer.......................... Date..............................
Dynamo No...................... Type............................
Normal output..........volts........amps., at........revs. per min.
Exciting current..............amperes.
Resistance between dynamo terminals (hot) ....ohms.

Load Current.		Revolutions per Minute $= n'$	Dynamo Voltage.		
Ammeter No........ Constant............			Voltmeter No.................. Constant		
Reading.	True Value.		Reading.	True Value $= V'$	Voltage* corresponding to Normal Speed $= V$.

---

* If the speed is not kept absolutely constant a correction must be made in the voltage observed.

Let n = revolutions per minute of armature at normal speed.
n' = revolutions per minute of armature at observed speed.
V' = voltage at observed speed (entered in 5th column).
V = voltage which would have been obtained at normal speed (entered in last column).

Then $V = \frac{n}{n'} V'$.

Keep the speed as constant as possible. Take speeds with the speed counter, if it is not possible to ensure a constant speed. Small variations in speed must be corrected for as described below the table. While the armature is still hot from the experiment, measure its resistance. This may be done by either of the methods described in C. II. In the case of small machines it is usually most convenient to find the resistance by passing through it a measured current from an external source, and measuring the voltage at the same time across the terminals, as described in Experiment I. The total resistance between the terminals (including the resistance of the brushes, &c.) is then the quotient of the voltage divided by the measured current. This is the resistance required.

Results of the test should be entered as in the table on page 59.

The results of Experiment VI. should be shown graphically on a curve, current being measured horizontally and voltage vertically, as shown in Fig. 14, p. 51, which represents a curve obtained from a 2-pole Crompton dynamo.

By drawing a horizontal line A B through the point of the curve corresponding to no-load voltage, the drop of voltage for any current may be measured downwards from this horizontal line.

In order to separate the drop in volts due to the resistance of the conductors from the drop due to the magnetic reaction of the armature current, it is necessary to draw the line A C as described on pages 51 and 52.

In the case of the dynamo for which Fig. 14 was drawn the resistance between the terminals after a run was found to be ·18 ohm. Accordingly, with 20 amperes the drop due to the resistance of the conductors was 3·6 volts, as indicated by the length of *b c*, measured downwards on the ordinate corresponding to 20 amperes.

Any ordinate now drawn from the horizontal line A B to the curve will be divided into two parts where it is cut by the line A C. The length of the upper portion gives the electrical or ohmic drop, the length of the lower part represents the drop due to magnetic reactions alone.

It should be noted that the ohmic drop represents a direct loss of power. The power lost, measured in watts, is the product of the current and drop of voltage. At full load of 20 amperes this quantity is represented on the diagram by twice the triangular area A *b* *c*, since this area is equal to $\frac{1}{2}$ A *b* × *b* *c*, and A *b*, *b* *c* represent the current and drop of voltage respectively. The power is spent in heating the armature conductors, commutator, &c.

The magnetic reactions do not directly involve any loss of power. They necessitate, however, a larger exciting current on the electro-magnets, with a corresponding increase in power necessary for excitation. Since they affect unfavourably the constancy of the voltage, they are undesirable. The magnetic reactions must always be kept low if the dynamo is to run without sparking.

Referring to the curve given on Fig. 14, it will be noticed that at first the fall of voltage is almost entirely due to drop in the armature conductors, since the curve and the line A C, showing the ohmic drop, are nearly coincident. At a load of 8 amperes the curve takes a decided bend downwards, ceasing to follow the line A C. The explanation of this sudden bend is that the brushes had remained nearly in the neutral position up to this point. With a load of 8 amperes it became necessary to move them round, thus increasing the demagnetising field as explained above. From this point the brushes were moved a little each time the load was increased in order to prevent sparking. Hence the weakening effect of the armature field increased rapidly with the increasing load.

On account of the effect of moving the brushes upon the voltage of the machine, care must be taken in all tests to regulate the position of the brushes gradually as it becomes necessary, and not in large steps at irregular intervals, which might produce irregular variations in the voltage of the machine.

The weakening of the field by the armature current can be calculated from the loss of voltage produced by it, as indicated on the curve.

Thus in Fig. 14, at the full load of 20 amperes, the length *c d* corresponding to the reactive drop is 12·5 volts, or 10·4 per cent. of the ordinate corresponding to the full voltage of 120·5 volts. We can say, therefore, that the field has been actually weakened to the extent of 10·4 per cent.

For practical purposes it would be more useful to determine the additional strength of field which would be necessary to maintain the voltage of the dynamo constant, or to prevent its falling below a certain value.

This can be done by noting what proportion the drop for the assigned current bears to the total voltage of the dynamo. The field strength would have to be increased in this proportion if it is desired to keep the voltage at the initial value. But this does not represent a proportional increase in excitation.

In order to ascertain the increase in magnetising force, or ampere-turns, necessary to produce a given increase in the magnetic field, or a given increase in voltage, reference must be made to the magnetisation curve already obtained. (See Fig. 12, p. 39.)

From this curve can be seen the number of additional ampere-turns necessary to increase the voltage by any required amount. Suppose, for instance, the number of ampere-turns already on the machine to be 3,000. If it is required to increase the voltage by 15 volts to make up for armature reaction at full load, the extra number required will be found from the curve on Fig. 12 by noticing the additional excitation required above that already applied to produce the no load voltage of 120·5.

On the curve 120·5 volts corresponds to an excitation of 1·07 amperes. The number of turns is 2,800. An increase of 15 volts, that is, a total of 135·5 volts, corresponds to 1·4 amperes, consequently the increased excitation required is ·33 amperes or $\cdot 33 \times 2{,}800 = 924$ ampere-turns.

Another experiment by which similar results may be obtained is the next one to be described. In this case the voltage is maintained constant by alteration of the exciting current, while the armature current is varied.

Experiment VII.—VARIATION IN EXCITING CURRENT OF A SEPARATELY EXCITED DYNAMO TO MAINTAIN CONSTANT VOLTAGE.

DIAGRAM OF CONNECTIONS.—As for Experiment VI., page 58.

Connections.—As for Experiment VI., page 58.

Instructions.—The voltage as read on voltmeter V is to be kept constant throughout the experiment by varying the resistance R_2 in the exciting circuit.

Before closing the main switch S_1, read the voltage on V. Close S_1 and adjust the voltage to the previous value. By successive steps increase the current by decreasing R_1 until the dynamo gives its maximum current, the voltage being kept constant.

For each value of the current, read the current in the exciting circuit on A_2 and the main current on A_1.

Move the brushes, as required, to avoid sparking.

Maintain the speed constant throughout.

Enter results as in the following table :—

DETERMINATION OF VARIATION IN EXCITING CURRENT OF A DYNAMO REQUIRED TO MAINTAIN CONSTANT VOLTAGE.

Observer.............................. Date.........................

Dynamo No........................ Type.........................

Normal output ....amps..............volts.

Normal speed..................revs. per minute.

Voltage maintained at terminals ....

Armature Current. Amperes.		Exciting Current. Amperes.	
Ammeter No. .... Constant..........................		Ammeter No. .... Constant	
Reading.	True Value.	Reading.	True Value.

The results should be plotted to form a curve as in Fig. 18, p. 64, the load current being measured horizontally, and the exciting current vertically.

If it is not possible to keep the speed exactly constant, a correction should be made by the aid of the magnetisation curve of the machine. Thus, if the speed falls, the excitation supplied to maintain the voltage constant will be greater than would have been necessary at normal speed. If the speed is found to have fallen x per cent., the field strength must have been increased by x per cent. above the value it would have had at normal speed. This does not mean an increase of x per cent. of exciting current, but a rather greater increase, which can only be exactly determined by reference to the magnetisation curve.

For small variations of speed, it will be sufficiently accurate to assume that the correction to be applied to the exciting current is proportional to the variation in speed.

Knowing the number of turns round the magnets, the vertical scale may be plotted in terms of either amperes or ampere-turns.

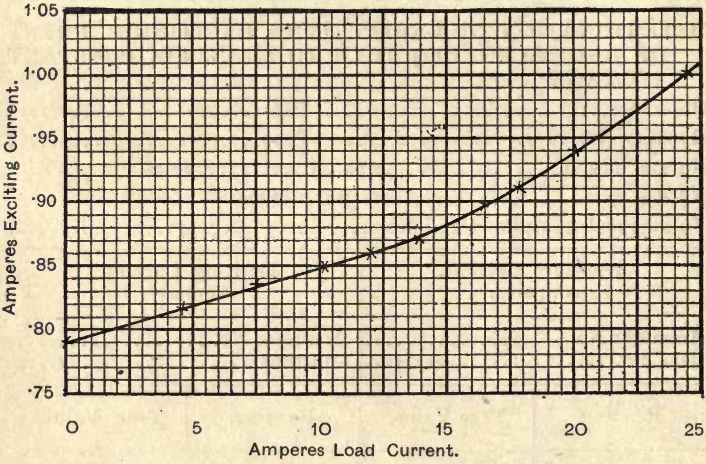

FIG. 18.—VARIATION IN EXCITING CURRENT TO MAINTAIN CONSTANT VOLTAGE. Voltage 100. Speed 1,400 revs. per minute. Number of magnet windings, 2,826

In this curve the initial portion is straight, showing that the fall of voltage to be counteracted increases regularly with the load at first, and that the field magnets are not saturated, so that the field is strengthened in the same ratio as the exciting current. Later, the curve bends upwards, owing to the magnets becoming saturated, and their permeability becoming less, and also owing to the decrease in armature voltage becoming more rapid as the load gets heavier. This, as already explained, is largely due to the increased lead of the brushes, and consequent weakening of the field.

The results obtained according to the method of either of the last two experiments are of use in determining the number of *series windings* required for a *compound-wound* dynamo required to maintain a constant voltage.

In a *compound* dynamo the magnet windings consist chiefly of shunt windings supplied with current from a source of nearly constant electromotive force. In addition to these windings are added a smaller number of turns through which the armature current flows—these are the *series windings*. The shunt windings supply a practically constant number of ampere-turns: the ampere-turns of the series windings increase in direct proportion with the armature current. This is more fully explained later in connection with the characteristic curve of a compound dynamo.

Magnetisation Curve of a Dynamo Under Load.—The magnetisation curve determined in Experiment V. (page 38) will only give the relation between voltage and magnetising current when the armature is not supplying current.

Since a machine is usually specified to give a certain voltage at full load, it is often necessary to determine the relation between its voltage and ampere-turns while giving its maximum working current. The next experiment is the determination of the magnetisation curve of the dynamo while the armature is giving current.

Experiment VIII.—MAGNETISATION CURVE OF DYNAMO UNDER LOAD.

DIAGRAM OF CONNECTIONS.—As for Experiment VI., Fig. 17, page 58.

Connections.—As for Experiment VI., page 58.

Instructions.—Keep the armature current, as read on ammeter A_1, constant throughout the experiment by varying R_1 when necessary. Also keep the speed constant.

Increase the exciting current from zero to its maximum value by decreasing the resistance R_2. For each value of the exciting current read the dynamo voltage on the voltmeter V.

Take a similar set of readings with decreasing values of the exciting current.

If necessary, correct for speed variation as before.

The results should be entered in tabular form as shown on page 66.

Plot a curve showing the dependence of voltage upon exciting current, plotting voltage vertically and excitation horizontally.

DETERMINATION OF MAGNETISATION CURVE OF A DYNAMO UNDER LOAD.

Observer.......................... Date.........................
Dynamo No. .... Type ....
Normal output ....volts........amps., at........revs. per min.
Armature Current during experiment..............amps.
No. of turns on magnets..........

Exciting Current.		Revolutions per Minute.	Armature Voltage.	
Ammeter No. .... Constant			Voltmeter No. .... Constant................	
Reading.	True Value.		Reading.	True Value.

Fig. 19, Curve II., is a curve obtained as described.

The upper Curve I. on the same figure shows the magnetisation curve obtained with the same machine according to the method of Experiment V., *i.e.*, without current in the armature. The difference between the curves is due to the armature reactions.

The voltage, measured vertically between the curves, shows in another manner the effect of armature reactions on the voltage of the machine.

During the experiment recorded in Fig. 19 the brushes were kept at the same angle of lead. Since the armature current was also kept constant, the armature reaction was maintained at the same value throughout. The effect upon the voltage of the dynamo was not constant, however; at least, this is true of the magnetic reactions. The loss of voltage due to ohmic drop in the armature conductors was constant, since the current was kept the same. In the experiment this was found to be 13 volts. The dotted line (Curve III.) is drawn above Curve II. at a uniform distance corresponding to 13 volts. Consequently the vertical distance between Curves I. and III. represents the drop due to *magnetic* reactions alone. At the lower part of Curve III. the loss of voltage is nearly 20 volts,* due to magnetic reactions. Hence at this point 13 volts are spent in overcoming armature resistance, nearly 20 volts are lost owing to the demagnetising effect of the armature current, and about 19 volts only are left at the dynamo terminals. At points higher on the curve

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* A small portion of this loss of voltage will be due to losses in commutation. This is neglected in the discussion.

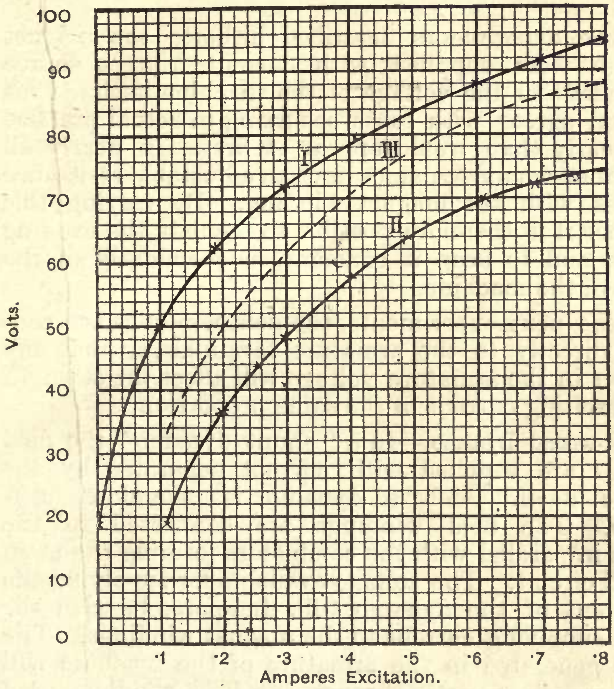

FIG. 19.

I.—Magnetisation curve at no-load.
II.—Magnetisation curve at full load.
III.—Total voltage generated in armature at full load.

the effect of the armature demagnetisation is less, since the permeability of the armature core and poles is less, due to saturation. Hence, although the demagnetising magneto-motive force is the same, its effect upon the voltage is less. Consequently the Curves I. and III. approach each other.

At the top part of the curves they recede from each other again to a slight extent. This is probably due to secondary actions, such as the increased magnetic leakage, demagnetisation due to eddy currents in the armature core at higher densities, and, perhaps, partly also to over-saturation of the yoke or some other portion of the magnetic circuit.

CHAPTER VI.

SHUNT-WOUND DYNAMO.

In the experiments described hitherto the magnet windings were supplied with current from a source independent of the voltage of the machine itself. This condition agrees with cases occurring in actual practice more nearly than would appear at first. In nearly all cases shunt-wound dynamos have an adjustable resistance in series with the magnet winding. By varying this resistance it is therefore possible to regulate the exciting current, and to keep it constant, independently of the voltage of the machine.

In the next experiments, the field windings are connected directly to the armature terminals, so that any variation in the armature voltage will affect the strength of the exciting current in the same proportion.

Shunt-wound Dynamo.—In a "shunt dynamo" the field windings are supplied with current generated by the machine itself. Such a dynamo is, therefore, *self-exciting*. The field windings are connected to the brushes in parallel with the conductors forming the main external circuit. The voltage available for supplying the load curent of the dynamo will, therefore, be also the voltage supplying current to the magnet windings. The current generated in the armature of the machine will divide, and flow partly through the field windings, and partly through the main circuit. The current spent in excitation will be useless so far as the output of the dynamo is concerned, and is made to be only a small fraction—say, from 1 to 3 per cent.—of the total current.

Variations in the speed of a shunt-wound dynamo affect the voltage in a twofold manner. Since the armature conductors make fewer revolutions, the voltage will fall, and this will reduce the pressure sending current through the magnet windings. The exciting current and strength of field will therefore also be reduced. Since the strength of field does not increase regularly in proportion to the ampere-turns on the magnets, the voltage of a shunt machine does not vary with the speed according to any simple law.

Experiment IX.—DETERMINATION OF THE RELATION BETWEEN VOLTAGE AND SPEED OF A SHUNT-WOUND DYNAMO.

DIAGRAM OF CONNECTIONS.

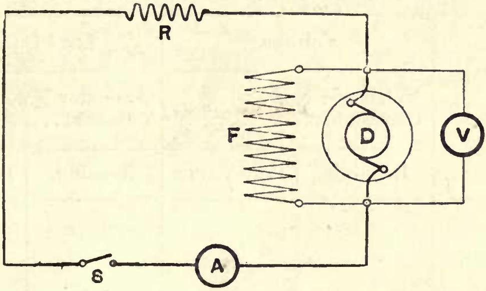

FIG. 20.

D	Dynamo armature.
F	Dynamo field windings.
R	Adjustable resistance for regulating the load.
A	Ammeter for measuring load current.
V	Voltmeter for measuring dynamo voltage.
S	Switch for breaking main circuit.

Connections.—Connect the shunt winding to the armature terminals, so as to render the machine self-exciting.

Connect a voltmeter across the armature terminals.

Connect the main terminals to a variable resistance in series with an ammeter and switch.

Instructions.—First open switch S so that the load is nil. Take readings on the voltmeter for several speeds.

Then close the switch, so that the dynamo gives current, and repeat the readings at the same speeds as before.

Take several series of readings, each series corresponding to a certain load.

At the beginning of each series move the brushes forward, if necessary, to prevent sparking.

The results should be entered as in the following table:—

DETERMINATION OF DEPENDENCE OF VOLTAGE ON SPEED IN SHUNT DYNAMO.

Observer .... Date ....
Dynamo No. .... Type ....
Normal output........volts.........amps., at........ revs. per min.

Revolutions per Minute.	Voltage.		Load Current.	
	Voltmeter No. .... Constant...............		Ammeter No. .... Constant...............	
	Reading.	True Value.	Reading.	True Value.

Plot curves showing dependence of volts upon speed, plotting a separate curve for each value of the load. Measure speed horizontally and voltage vertically.

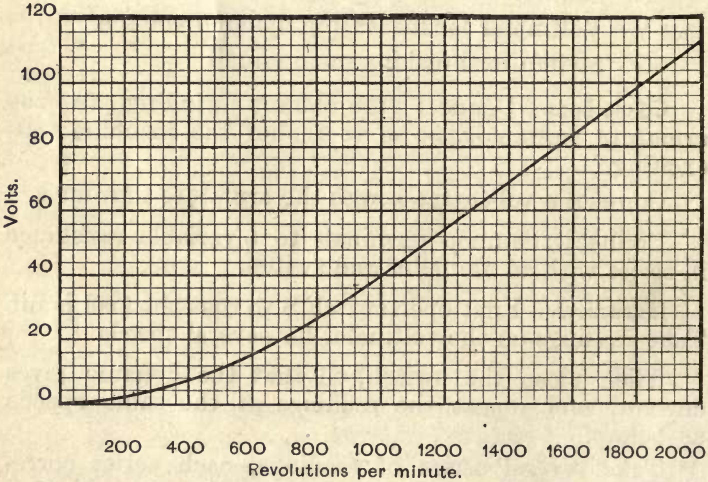

FIG. 21.—CURVE SHOWING DEPENDENCE OF VOLTAGE OF A SHUNT DYNAMO ON SPEED.

The curve shown in Fig. 21 gives the results of a test carried out at no-load on a 2-pole dynamo, whose normal speed is 1,600 revs. per minute. The curve becomes practically a straight line for speeds above 900 revs.

per minute. Above that speed both speed and voltage increase in a fairly constant proportion of 1 volt for 13·6 revs. per minute.

The form of the curve for any given machine will depend upon the shape of the magnetisation curve, but usually a simple approximate relation may be found connecting variations of speed and voltage where the variations from the normal are not great.

In the region of speeds likely to occur in practice, the straight portion of the curve given in Fig. 21 satisfies approximately the equation

$$V = \frac{S - 460}{13{\cdot}6}$$

When V = voltage and S = revolutions per minute.

Characteristic of a Shunt Dynamo.—The curve usually termed the *Characteristic Curve* of a dynamo is one giving the relation between the voltage and load of the machine when running at its normal speed. It is a curve in which the vertical scale represents volts, and the horizontal scale amperes. Such a curve is of very great use, since it shows completely what output the machine may be made to give. It has also other uses, as will shortly be pointed out.

Experiment X.—DETERMINATION OF THE CHARACTERISTIC CURVE OF A SHUNT-WOUND DYNAMO.

DIAGRAM OF CONNECTIONS.

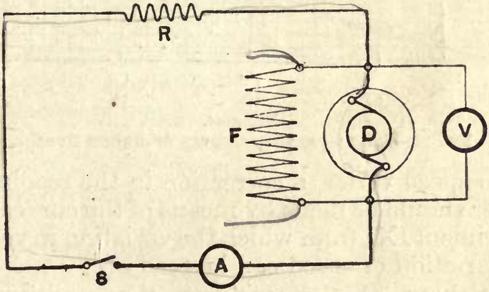

FIG. 22.

D	Dynamo armature.
F	Dynamo field windings.
R	Adjustable resistance for varying the load.
A	Ammeter for measuring load current.
V	Voltmeter for measuring dynamo voltage.
S	Switch for breaking main circuit.

Connections.—See that the shunt winding is connected to the brushes of the dynamo.

Connect the main terminals to a variable resistance, including in the circuit an ammeter and switch.

Connect a voltmeter to the armature terminals.

Instructions.—Begin with the switch open, so that the load is nil. Then increase the load gradually by first closing the switch and then decreasing the resistance R.

For each value of the load, read the ammeter A, voltmeter V, and the speed.

The speed should be kept as nearly constant as possible.

The machine should have been running for some time before readings are taken, to avoid errors due to alteration in the resistance of the windings when heated.

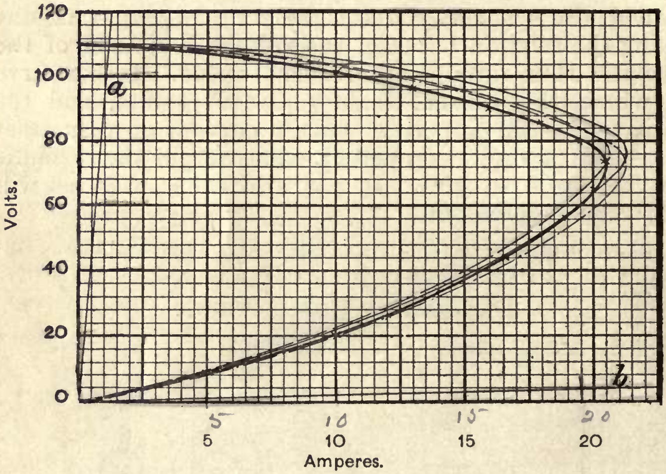

FIG. 23.—CHARACTERISTIC CURVES OF SHUNT DYNAMO.

If the speed varies, a correction in the readings of the voltmeter should be made by means of the curves obtained in Experiment IX., from which the variation in voltage due to any variation of speed can be read off.

Throughout the experiment the position of the brushes should be adjusted so as to prevent sparking.

After completing the readings, and while the windings are still hot, determine the resistance of the armature and field windings, as described in Experiments I.—III., pages 6 to 17.

Results should be recorded as shown in page 73.

DETERMINATION OF THE CHARACTERISTIC OF A SHUNT DYNAMO.

Observer........................ Date..........................

Dynamo No..................... Type..........................

Normal output..........volts........amps., at........revs. per min.

Resistance of armature (hot)..............ohms.

Resistance of field windings (hot)........ohms.

Load Current.		Revolutions per Minute $= n^1$	Voltage.		
Ammeter No........ Constant...........			Voltmeter No. .... Constant		
Reading.	True Value.		Reading.	True Value $= V^1$	Voltage* corresponding to Normal Speed $= V$.

Plot a curve showing the dependence of voltage (corrected, if necessary, to make it correspond to normal speed) upon load.

The curve in Fig. 23, drawn as a continuous thick line, shows a characteristic curve obtained from a 2-pole Crompton dynamo. The fall in voltage which the curve shows with increased currents is due both to the ohmic drop in the armature conductors, and also to the magnetic armature reactions which increase with the load. This decrease in the voltage available for supplying current to the magnets causes a decrease in the exciting current, and a decrease in the field strength, and consequently a further drop in voltage. The curve may be compared with the curve shown in Fig. 14, p. 51, obtained from the machine when excited with constant current from an external source, at a slightly higher voltage. The difference between two curves taken from the same machine under these conditions will show the effect of the lessened excitation of the shunt dynamo at heavy loads.

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* If the speed does not remain constant during the experiment a correction must be made by the aid of the curve corresponding to the same load obtained in Experiment IX.

For most purposes the curve would only be obtained for currents having values between zero and the maximum which the machine was intended to give out. In the curve given in Fig. 23 this would be the upper portion of the curve corresponding to loads between 0 and 17 amperes.

If the resistance in the circuit be decreased beyond these values, further readings on the curve are obtained. The curve slopes downwards more and more steeply, and finally becomes vertical, *i.e.*, the voltage corresponding to a given load becomes unstable. If the resistance of the circuit be carefully and gradually decreased still further, the curve will be found to bend back towards the origin. When gradually short-circuited, the dynamo gives no voltage and no current, or only a small current, on account of its possessing some residual magnetism.

It is thus found that the machine will give either of two voltages for any particular strength of current, depending on the resistance in the external circuit.

Judgment must be used in taking the complete shunt characteristic, as in some cases the current in the armature may be sufficient to overheat it. Also with some machines the sparking which occurs at the brushes becomes injurious when the voltage falls considerably.

Total Characteristic.—The curve described above, and shown as a full line in Fig. 23, p. 72, is the "external characteristic."

7 The *external characteristic* of a dynamo is obtained by measuring the current in the external circuit, and the voltage between the dynamo terminals.

From this curve may be derived another, called the "total characteristic," or "internal characteristic." The *total characteristic* shows the relation between the total current flowing in the armature and the total voltage generated. The total current includes the current flowing in the field windings as well as the external current. The total voltage includes the volts "lost" in the armature owing to its resistance, in addition to the voltage measured at the terminals. The exciting current is proportional to the dynamo voltage, and the "lost" volts in the armature are proportional to its current.

The current spent in excitation at various voltages may be represented on the same sheet of paper as the characteristic curve, by a straight line passing through the origin of co-ordinates.

In the case of the machine from which Fig. 23 was drawn, the resistance of the field windings was 95 ohms when hot. At 100 volts the exciting current was, therefore, $\frac{100}{95} =$ 1·05 amps. On the vertical line corresponding to 100 volts, a length equal to 1·05 amps. was marked off, and the line joining this point, *a* to O, shows the current taken by the field winding at any voltage of the dynamo. For any voltage the exciting current is given by the horizontal distance of O *a* from the vertical axis, measured at the height corresponding to that voltage.

Similarly the volts lost in the armature at any load may be indicated by a second straight line O *b* drawn through O.

Thus (see Fig. 23) with an armature resistance of ·18 ohms the loss in voltage at 20 amps. will be $·18 \times 20 = 3·6$ volts. The line O *b* is consequently drawn through the point *b*, corresponding to 20 amps. and 3·6 volts. The ordinates of this line represent the loss of voltage at any load.

From the external characteristic, shown as the thick-line curve in Fig. 23, may be derived three other curves.

Curve 1 shows the dependence of the terminal voltage on the total armature current (= load current + exciting current). This curve is shown in long and short strokes. It is derived from the experimental curve by adding to the observed current the corresponding exciting current. The curve lies at each point exactly as far to the right of the original curve as the line O *a* is to the right of the vertical axis at the corresponding voltage of the machine.

Curve 2 shows the relation between load current and total voltage (= observed voltage + voltage lost in the armature).

This curve (shown in long dashes) is obtained from the observed characteristic by adding to each ordinate a length equal to the height of O *b* above the horizontal axis at the load considered; thus adding the "lost" volts to the observed voltage in each case.

Curve 3 is the *total characteristic*, and is shown in Fig. 23 by a fine continuous line. It shows the relation between the total current flowing in the armature and the total voltage generated.

In deriving this curve from the experimental external characteristic, each point is taken higher than the corresponding point on the external characteristic by an amount equal to the armature drop, and further from the vertical axis by an amount equal to the exciting current.

The method of drawing the total characteristic after obtaining the external curve is as follows: From any point, *p*, on the external characteristic draw a horizontal line equal in length to the distance of O*a* from the vertical axis at the height above the horizontal axis of the point *p*.

From the end of the line so drawn, draw a vertical line upwards equal in length to the height of the line O *b* above the base line at the load corresponding to *p*. The end of this line will be a point on the required curve.

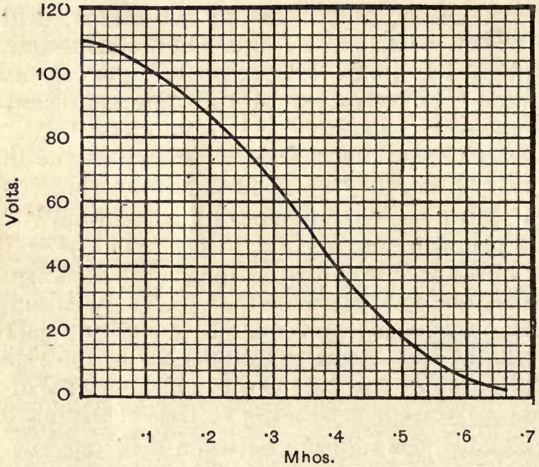

FIG. 24.—CONDUCTIVITY CHARACTERISTIC OF SHUNT DYNAMO.

The horizontal distances between the total and internal characteristics is proportional to the current spent in the machine; also the vertical distance between the curves is proportional to the voltage lost. The area enclosed between them is proportional to the product of amperes × volts wasted in the dynamo.

The area between the internal and external characteristic curves is consequently proportional to the power lost in the machine. Consequently the more nearly the two curves coincide, the higher is the efficiency of the dynamo.

Usually the field magnets will possess a certain amount of residual magnetism which will enable the dynamo to send current when the terminals are short-circuited and the exciting current is zero. This will be shown by the characteristic cutting the horizontal axis at some point to the right of O, indicating that there is current flowing although the voltage at the terminals is too small to be observed.

Resistance Characteristic.—The results of Experiment X. should also be plotted in another way, namely, on a curve showing the dependence of the voltage upon the conductivity of the external circuit. The resistance of the circuit will be the value of the fraction

$$\frac{\text{volts measured at dynamo terminals}}{\text{current in circuit}}.$$

The conductivity of the circuit is

$$\frac{1}{\text{resistance of circuit}} = \frac{\text{current in circuit}}{\text{dynamo voltage}}.$$

The name given to the unit of conductivity is the *mho*, representing the inverse of the ohm.

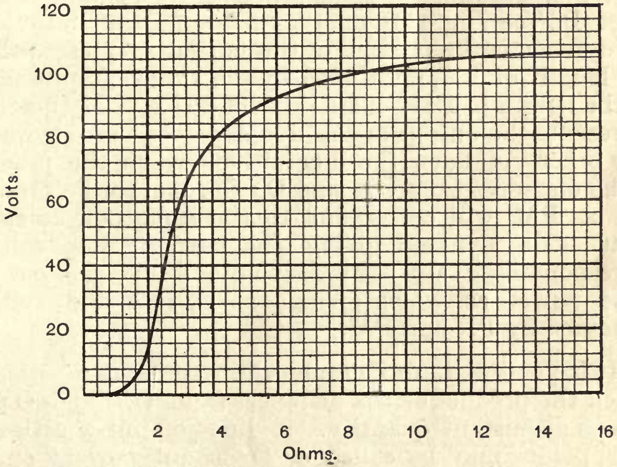

FIG. 25.—RESISTANCE CHARACTERISTIC OF SHUNT DYNAMO.

For each value of the current the conductivity should be calculated and its values plotted horizontally, the corresponding voltage being measured vertically. In this manner the curve in Fig. 24 has been obtained from the results recorded in Fig. 23.

The curve shows that whenever the circuit resistance alters (as by the switching on of lamps in a lighting circuit) the voltage of the dynamo will vary, no part of the curve being horizontal, although it is nearly so at the upper part of the curve, when the conductivity is very small.

The curve may equally well be plotted with *ohms* instead of *mhos* as base, so as to show dependence of voltage on the resistance, instead of conductivity, of the main circuit. This is shown for the same observations in Fig. 25, from which similar deductions might be made.

Power Curves.—Here it may be well to explain a method of adding to any characteristic curve a series of lines showing at a glance the amount of power given out by the dynamo when working under conditions corresponding to any point on the characteristic.

The power given out by a dynamo is measured in watts, *i.e.*, by the product of the current and voltage measured at the terminals (= volts × amps.)

When working under conditions corresponding to any point P (see Fig. 26) on the diagram, the output of the dynamo is the product of the current, represented by the length of PN, multiplied by the voltage, represented by the length of PM. The product PN × PM therefore represents the output of the dynamo measured in watts. Any other points on the diagram for which the product of the distances from OX and OY is equal to the product PN × PM will correspond to the same output as P. That is, a dynamo giving the current and voltage corresponding to any of these points would give out the same power as when giving the current and voltage measured by PN and PM.

It is possible to find graphically a series of points for which the product of the distances from OX and OY is always a constant quantity. A line joining a series of such points may be called a "constant power" curve, since all points on the curve correspond to the same number of watts. The curve will be a rectangular hyperbola, the peculiarity of which is that the rectangles formed by drawing horizontal and vertical lines from any point on the curve to cut the co-ordinate axes will always have a constant area.

A number of such curves have been drawn in Fig. 26, each corresponding to a definite output, namely, 1, 2, 3, and 4 h.p. respectively.

The method of drawing a curve of constant power through any point P is as follows :—

Through P draw horizontal and vertical lines PN, PM, to meet the co-ordinate axes in N and M (see Fig. 26). Through O, the intersection of the axes, draw any line O *b* *a*, cutting NP and MP in *b* and *a* respectively. Through *b* and *a* draw vertical and horizontal lines intersecting in Q. Q is a point on the curve. By

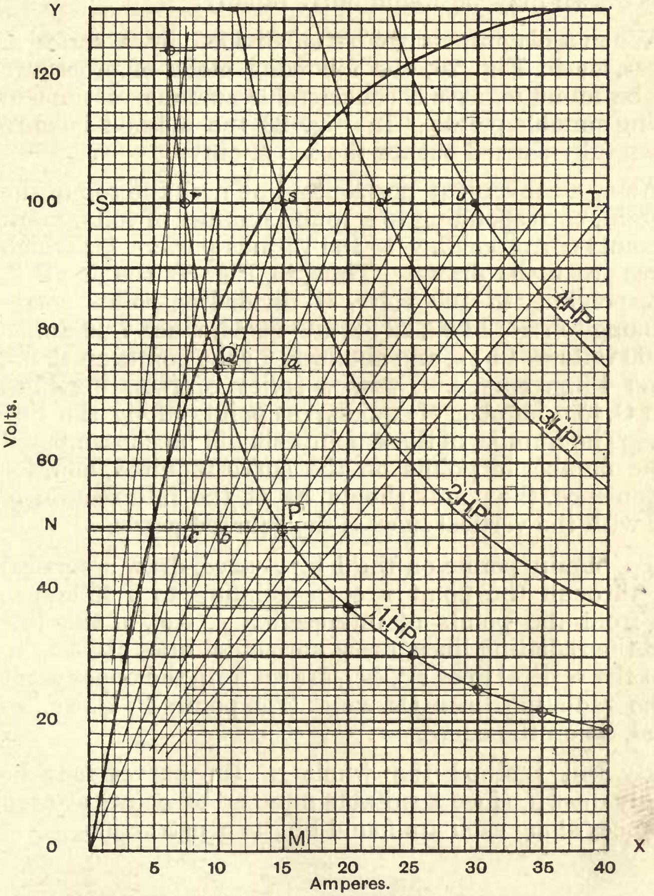

FIG. 26.—METHOD OF DRAWING HORSE POWER CURVES.

drawing other lines through O, making different angles with the base line, other points may be obtained. Horizontal and vertical lines may be drawn from any of the points so found in order to determine fresh points exactly as described for the point P. Since the horizontal and vertical lines can be drawn with Tee and set squares, sufficient points to enable a complete curve to be drawn may be found fairly rapidly.

When a diagram is to be subdivided by a series of curves, as in Fig. 26, the following mode of procedure will be found to save a considerable amount of time in finding suitable points. In Fig. 26 the method is only shown fully carried out for the 1 h.p. curve.

Along a convenient horizontal line near the top of the diagram, corresponding to a round number of volts, mark off points corresponding to the various powers for which curves are to be drawn. Thus, in Fig. 26, the line S T, corresponding to 100 volts, is divided at points corresponding to 7·46, 14·92, 22·38, and 29·84, since 7·46 amps. × 100 volts = 1 h.p., and similarly for the points on the 2, 3, and 4 h.p. curves. Draw a series of radiating lines from O, to a number of equidistant points along the line S T. The number of these points should be chosen equal to the number of points on the curve required, and, for convenience, the points should be at the intersection of S T, with the vertical lines of the squared paper.

To obtain points on the 1 h.p. curve, draw a vertical line through the point *r* corresponding to 7·46 amps., and from the points of intersection *c*, &c., of this line with the radiating lines, draw horizontal lines *c*P, &c., to meet the vertical lines *s*P, &c., drawn from the upper point of the radiating lines O*c*, &c. The points P, Q, &c., so found, lie on the curve.

By this method the whole of the curves may be rapidly drawn, since a suitable number of points at even distances along each are found by the construction.

CHAPTER VI.

THE SERIES DYNAMO.

Characteristic of a Series-wound Dynamo.—In the experiments so far described, the field magnets were either independently excited, or were connected to the armature of the dynamo so as to receive current from it at the voltage of the external circuit. In one case the dynamo was "separately excited," and in the other case the dynamo was "shunt excited," the field windings forming a parallel circuit, or shunt, to the main circuit. In a shunt dynamo the current generated in the armature divides, and flows partly round the magnets and partly through the external circuit. The current employed in excitation varies only with the *voltage* of the machine.

In a **series dynamo** the entire current flows through the field coils, which are connected in series with the main circuit. In this case, an increase of load means an equal increase in the exciting current. The excitation, therefore, depends upon the *load* and increases with it. The voltage of the dynamo will therefore be higher at full load, and the "characteristic" of a series dynamo must be a rising curve.

Experiment XI.—DETERMINATION OF THE CHARACTERISTIC CURVE OF A SERIES-WOUND DYNAMO.

DIAGRAM OF CONNECTIONS.

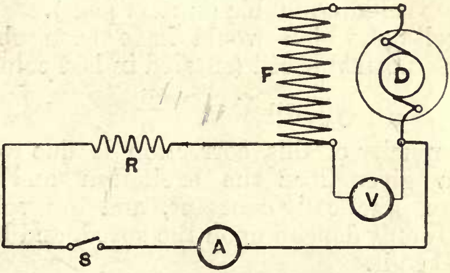

FIG. 27.

D	Dynamo armature.
F	Dynamo field windings.
R	Adjustable resistance for varying the load.
A	Ammeter for measuring load current.
V	Voltmeter for measuring dynamo voltage.
S	Switch for breaking main circuit.

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Connections.—See that the field windings are connected so that the whole of the current passes through them. In circuit with the armature connect a variable resistance, an ammeter, and a switch. Connect a voltmeter to the armature terminals.

Instructions.—Adjust the resistance R to its maximum value. Close switch S, slowly decrease R until the dynamo gives its maximum current. Then decrease the load gradually by increasing the resistance R, taking readings of load current, voltage, and speed for each value of the load. Take a similar series of readings while gradually increasing the load to its former value. The speed should be kept constant.

Throughout the experiment the position of the brushes should be adjusted so as to prevent sparking.

Immediately after completing the readings, and while the windings are still warm, determine the resistance of the armature and field windings according to one of the methods described in Experiments I. to III., pages 6 and seq. Observe whether the speed varies during the experiment.

If the speed does not remain constant during the experiment, a correction must be made as follows:—

Let n = revolutions per minute of armature at normal speed.
n^1 = revolutions per minute of armature at observed speed.
V^1 = voltage at observed speed (entered in fifth column of table on next page).
V = voltage which would have been obtained at normal speed (entered in last column).

$$\text{Then } V = V^1\frac{n}{n^1}$$

The simplicity of this correction is due to the fact that for a given load the excitation and armature reactions are practically constant, and the voltage will consequently only depend upon the speed, and be directly proportional to it.

In the table of results given below, the figures entered in the column headed "Voltage corresponding to normal speed" are to be obtained in this manner from those in the preceding column.

The method of entering up the results is as on the following page.

DETERMINATION OF CHARACTERISTIC CURVE OF A SERIES DYNAMO.

Observer.................................... Date...
Dynamo No................................. Type..
Normal output..............volts...........amps., at...........revs. per min.
Resistance of armature (hot) ....ohms.
Resistance of field windings (hot) ....ohms.

Load Current.		Revolutions per Minute. $=n^1$	Voltage.		
Ammeter No. .... Constant..................			Voltmeter No........................... Constant		
Reading.	True Value.		Reading.	True Value $=V^1$	Voltage corresponding to Normal Speed $=V$.

Plot a curve showing the dependence of voltage (corrected, if necessary, to make it correspond to normal speed) upon load.

The curve drawn as a full line in Fig. 28 (page 84) is the characteristic curve determined for a 2-pole series dynamo, 2½ kw. output, at 1,450 revs. per minute.

Horse-power curves, showing graphically the power of the dynamo, may be added on the same sheet as the characteristic, as explained in connection with the shunt dynamo. (See Fig. 26, page 79.)

The characteristic of a series dynamo is practically the same as the magnetisation curve, since the current of the dynamo plotted horizontally on the curve is also the exciting current. The only difference between the two curves is that the armature reactions reduce the voltage in the characteristic curve slightly below the values it would have on a curve taken without current in the armature.

In Fig. 28, the magnetisation curve taken without armature current is shown for comparison, the exciting current being derived from an external source. This is the Curve III. drawn in long and short dashes.

The volts represented by vertical distances between Curves I. and III. are partly "lost" in overcoming the resistance of the armature and series winding, and are partly voltage drop due to the demagnetising action of the armature currents. Curve II. drawn above Curve I., is obtained from it by adding the loss of voltage due to the resistance in the armature and field. Thus the difference between Curves II. and III. represents the effect of magnetic armature reactions. This is seen to be slight for the lower part of the curves. This is owing to the fact that both armature current and field current increase together, and when the magnetic path is unsaturated the demagnetising action of the armature is a constant fraction of the total magnetisation so long as the brushes are not shifted. Owing to the same cause it is unnecessary to shift the brushes much at light loads in the case of a series dynamo. As the magnets become saturated, the effects of armature reaction increase, and the brushes have to be moved forward, producing the considerable difference in the height of the two curves.

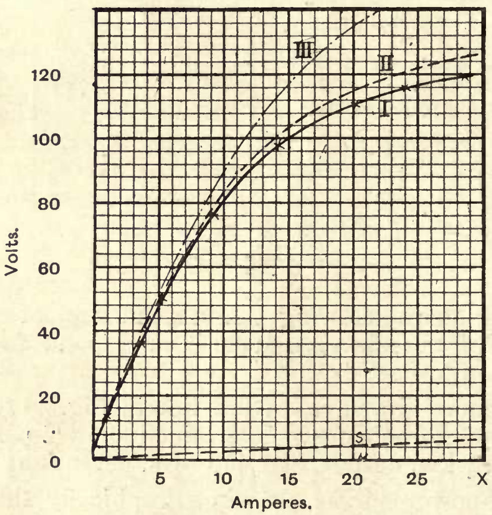

FIG. 28.—CHARACTERISTIC CURVE OF SERIES DYNAMO.

Curve I.—External characteristic.
,, II.—Internal ,,
,, III.—Magnetisation curve at no load.

The drooping of the characteristic is always greater if the magnets are weak, or if, being made of small section, they become highly saturated. It also occurs most in those machines in which the armature core is saturated, as this increases the magnetic leakage to a great extent. The permeability of the armature core becoming smaller owing to the core saturation, many of the lines of the field pass from pole to pole through the air, instead of through the armature.

Resistance Characteristic.—The results of this experiment should also be plotted as a curve showing the dependence of voltage upon the resistance of the external circuit, as described in the case of the shunt characteristic curve.

Such a curve, showing the results obtained from the same observations as Fig. 28, is shown on Fig. 30.

As an alternative, volts and mhos may be plotted, showing the same features of the behaviour of the machine. This has been done for the same readings on Fig. 29.

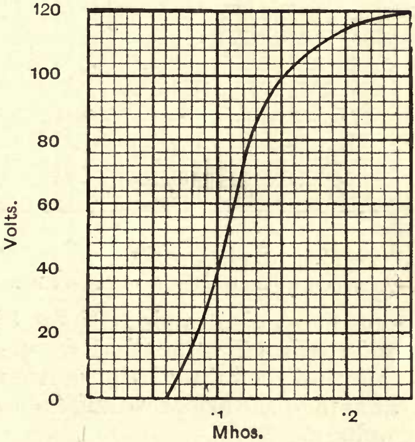

FIG. 29.—CONDUCTIVITY CHARACTERISTIC OF SERIES.

Total Characteristic.—As in the case of a shunt dynamo the *total* or *internal* characteristic may be determined from the observed external characteristic curve of a series dynamo.

The current will be the same in both internal and external characteristics. The difference between the observed volts and the total voltage generated in the armature will be the volts "lost" in the armature conductors and series field winding, through both of which the total current flows. For any particular value of the current this loss of voltage is the product of the current and joint resistance of the armature and field winding.

The method of obtaining one curve from the other is similar to that described for determining the "armature drop" in the case of the shunt characteristic. See Fig 28 (page 84).

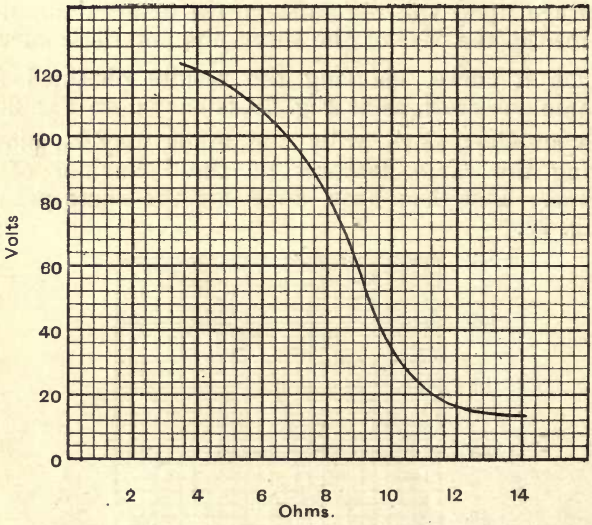

FIG. 30.—RESISTANCE CHARACTERISTIC OF SERIES DYNAMO.

Through any convenient point N on OX draw a vertical line, and mark off a length NS equal (on the scale of volts) to the product of the current ON (say 20 amps) and the sum of the armature and field resistances (in this case ·25 ohm).

Thus NS = 20 × ·25 = 5 volts.

Drawing the straight line OS, ordinates of this line represent the volts spent in the armature and field windings, which are not recorded on the voltmeter connected to the dynamo terminals.

The total characteristic is now obtained from the characteristic curve already drawn by adding to its ordinates lengths equal to the ordinates of the line OS. In this way Curve II. on Fig. 28 has been obtained.

It is interesting to compare three curves obtained, as already described, for a given machine.

(1) Magnetisation curve at no load with external excitation. (Experiment V., Fig. 12, page 39).

(2) Magnetisation curve with constant load current and external excitation. (Experiment VIII., Fig. 19, page 67).

(3) Series characteristic, load and excitation varying together. (Experiment XI., Fig. 28, page 84).

Arc-lighting Dynamos.—Series machines are often used for arc-lighting. In this case the arc lamps are connected in series, so that the dynamo is required to give a fairly constant current over a considerable range of voltage, depending upon the number of lights in use.

Many automatic devices for regulating the current by shifting the brush rocker, or varying the excitation, have been employed. These will not be discussed here, but one feature in the design of series dynamos for constant current may be referred to.

If the effects tending to produce a downward bend in the characteristic are sufficiently pronounced, the characteristic may be made to bend down so steeply that for considerable variations in voltage the current varies only slightly. In this way a drooping characteristic may be an advantage, if the machine be made to work on the drooping portion of the curve. An example of such a case is shown in Fig. 31 (page 88), the working part of the curve being between about 40 and 60 volts.

The chief causes producing a downward bend in the curve are : (*a*) Armature reaction, especially with a considerable forward lead of the brushes. (*b*) Saturation of magnets. (*c*) Magnetic leakage, especially that due to a saturated armature core. (*d*) Resistance of armature and field windings, which is sometimes purposely augmented by a resistance in series with them, when a drooping characteristic is desired.

Effect of Variation of Speed.—The horizontal scale in the characteristic of a series dynamo is a measure of the excitation as well as the main current. From this it follows that if the machine be run at a different speed while giving the same current, and consequently receiving the same excitation, the effect will be a variation in voltage proportional to the variation in speed (see Experiment IV). Thus a characteristic curve* taken when running at a speed 30 per cent. above the normal would be similar to the normal characteristic, except

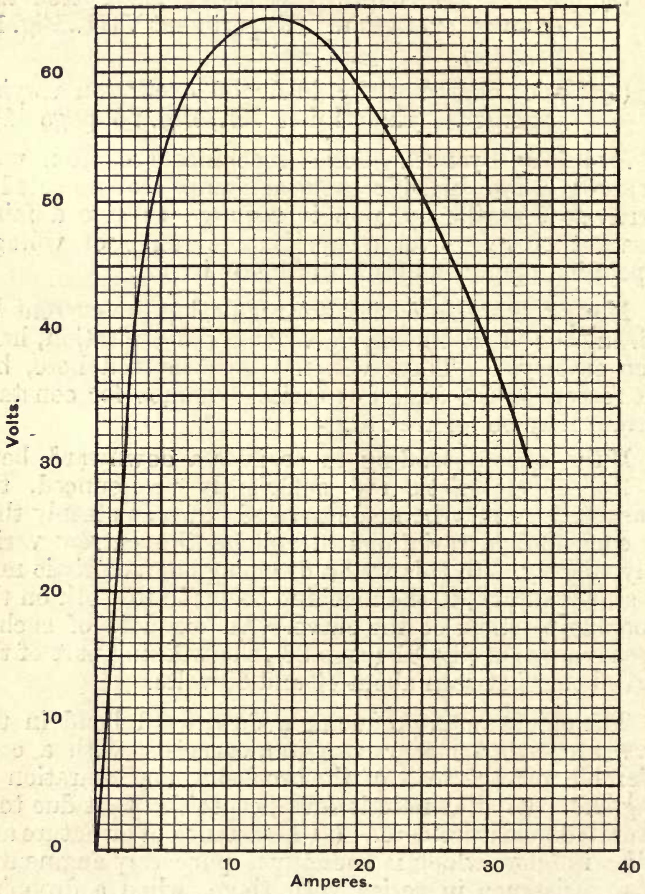

FIG. 31.—SERIES CHARACTERISTIC OF ARC LIGHTING DYNAMO.

that the height of all points on the curve would be 30 per cent. more. That is, the vertical scale would be altered in the same ratio as the speed, the horizontal scale remaining the same.

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* This is only strictly true of the total or internal characteristic. It is the total voltage generated which will vary in the same ratio as the speed.

CONDITIONS FOR SELF-EXCITATION.

Critical External Resistance for a Series Dynamo.—In a series dynamo it is the current flowing in the external circuit supplied by the machine which excites the field magnets If the main switch of the circuit is open, the resistance of this circuit is infinite and no excitation is possible. If the switch is closed, but the circuit has a high resistance, the current may still be insufficient to enable the dynamo to send enough current through the circuit to reinforce the residual magnetism of the field, and enable the machine to generate more current, so as to become self-exciting.

There is thus a certain maximum value of the external resistance which will just allow a series dynamo to become self-exciting. If the resistance be increased above this, the dynamo will not self-excite, while for any smaller value of the resistance the dynamo will always be self-exciting. This limiting value is called the *critical external resistance.*

From the characteristic curve of a series dynamo it is possible to ascertain what this maximum resistance is, above which the dynamo will fail to excite.

The critical resistance will vary if the dynmo is run at different speeds, since the characteristic curve only applies to a machine when running at one definite speed.

A dynamo will become self-exciting if the voltage necessary to produce its exciting current is not greater than the voltage generated by the dynamo. If under any conditions (for instance, an excessive resistance in the external circuit) the voltage required to maintain the exciting current becomes greater than the dynamo voltage, obviously the dynamo cannot itself maintain the excitation. The voltage of the dynamo will consequently fall, due to decreased excitation, and will ultimately become steady at a point slightly above zero, where it will be maintained by the residual magnetism of the fields.

Putting this into symbols,
Voltage necessary to produce exciting current

$$= e = c\,r; \quad \text{hence } r = \frac{e}{c}$$

where e = terminal voltage of dynamo
c = dynamo current
r = resistance in external circuit.

But the external characteristic (see Fig. 32) gives the relation between e and c. For instance, under conditions represented by any point, P, on the curve

$$e = \text{NP} \quad c = \text{ON} \quad \therefore r = \frac{e}{c} = \frac{\text{NP}}{\text{ON}} = \tan \text{POX} = \tan \alpha$$

if volts and amperes are both plotted to the same scale, and α is the angle made by OP with the horizontal.

Thus the external resistance is always represented by the tangent of the angle POX for any point, P, on the curve, when PO is the line drawn from P to the point of intersection of the axes. The circuit resistance for any point can be at once read off from a curve drawn on squared paper* by joining the point to the origin, O, and noting the point at which the line cuts the vertical through 1,

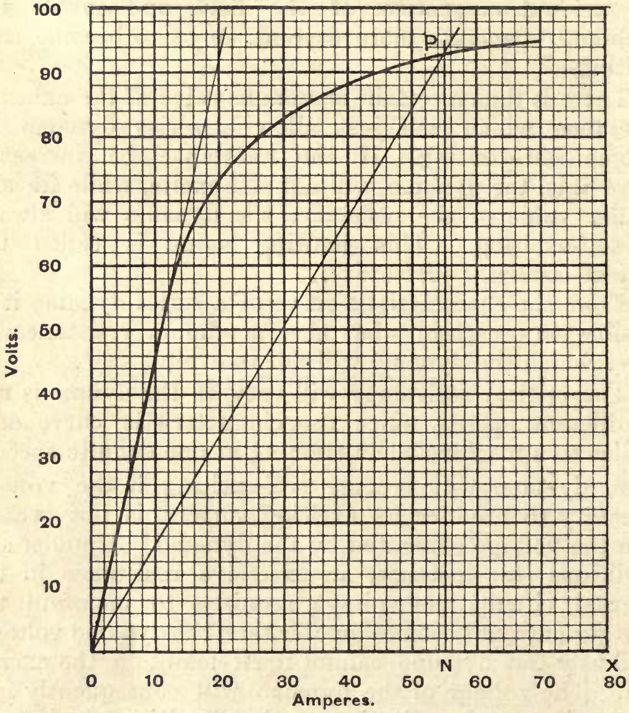

FIG. 32.—DETERMINATION OF THE CRITICAL RESISTANCE FROM THE CHARACTERISTIC CURVE OF A SERIES DYNAMO.

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* This construction may be carried out as described, whether the volt and ampere scales are the same or not.

10, or 100 amperes according to the scale, and dividing the voltage by the current for that point. Thus in Fig. 32, OP cuts the 10-ampere line at a point corresponding to 16·8 volts; consequently the external resistance is

$$\frac{16{\cdot}8}{10} = 1{\cdot}68 \text{ ohms.}$$

In a similar manner we may find the point on a characteristic curve (and consequently the voltage and current given by the dynamo) corresponding to a circuit of any given resistance. In this case, to reverse the example just given, let it be required to determine from the characteristic curve the current and voltage of the dynamo when supplying a circuit whose resistance is 1·68 ohms.

On the vertical line through 10 amperes mark off a point at a height $1{\cdot}68 \times 10 = 16{\cdot}8$, and join O to this point. The continuation of the line so drawn cuts the curve at P. The dynamo will consequently give 55 amperes at 93 volts under the conditions stated.

If the resistance of the external circuit is so high that the sloping line drawn from O becomes too steep to cut the curve, there will be no point on the characteristic fulfilling the necessary conditions, consequently the dynamo will be unable to excite its field, and the critical resistance is exceeded.

The characteristic of a series dynamo begins from O practically as a straight line. Any line drawn from O making a greater angle with OX than this initial portion of the curve will fail to cut the curve, and will represent by its inclination an external resistance greater than the critical resistance of the machine. A line drawn at the same inclination as this portion of the curve will coincide with the curve for some length; consequently, with a resistance corresponding to this inclination in the external circuit, the dynamo may have any output within a considerable range, the voltage and current being unstable. A line having a less inclination than this will always cut the curve at one definite point, and will thus indicate a resistance through which the dynamo will send a definite current at a definite voltage.

The inclination of a line drawn from O, and having the same slope as the initial portion of the characteristic curve, will therefore represent the critical external resistance of the dynamo. The exact value of this resistance in ohms may be read off at the point where this line cuts the vertical through 1 or 10 amperes. If read on the 10-ampere line, the reading must, of course, be divided by 10. In the curve on Fig. 32 the critical resistance is seen to be $\frac{45 \cdot 5}{10} = 4 \cdot 55$ ohms. If the dynamo is connected to a circuit having a resistance of more than 4·55 ohms, it will consequently not excite.

Critical Current.—In dealing with the conditions for self-excitation of a series dynamo, we may consider the *critical current* instead of the *critical resistance* in the external circuit, since for each value of this resistance the dynamo will produce a definite current, corresponding to the point at which the resistance line cuts the characteristic curve. When connected to a circuit having the *critical resistance,* however, the resistance line and curve coincide for some distance. The *critical current* is then the *maximum* current which the dynamo will send through this resistance. The *critical current* may be defined as follows: The critical current of a series-wound dynamo is the least amount of current which the dynamo will send through a circuit without losing its field magnetisation.

It must always be remembered that the critical resistance depends upon the speed of the machine, and will have a different value for every different speed.

As already pointed out (page 87), the effect of an alteration of speed upon the characteristic is practically equivalent to a change of the vertical scale (of volts), or to a proportional alteration in the height of every point on the curve, if the scale remains the same.†

From this it follows that the resistance of the external circuit corresponding to any point on the curve will also be increased or decreased in the same ratio as the speed of revolution. This must also apply to the critical resistance, which therefore changes in the ratio of the speed. Since the characteristic maintains its general shape irrespective of speed, the point at which the initial straight part ends will only change its position vertically with change of speed, and the *critical current* remains the same.

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† It is to be noted that this applies strictly only to the *total* characteristic curve. It applies very nearly also to the external characteristic in most machines, since the voltage lost in the armature and field windings is usually very small.

Putting these results briefly—the critical resistance changes in proportion to any change of speed, while the critical current remains the same irrespective of speed.

CHAPTER VII.

COMPOUND DYNAMO.

From the curves given in Figs. 23 and 28, it will be seen that the voltage of a shunt-wound dynamo falls as the load increases, whereas the voltage of a series-wound dynamo rises with increased loads.

By providing the magnets with a composite winding, consisting of partly shunt coils and partly series coils, an approximately uniform voltage at all loads may be obtained.

A dynamo provided with a composite winding in this way is called a *compound-wound*, or simply *compound*, dynamo.

Since the variation in voltage of a shunt dynamo is comparatively small at loads less than the maximum working current, the windings of a compound dynamo designed to give constant voltage will be similar to those of a shunt dynamo, with the addition of a comparatively few series turns to correct the slight variation which would occur in a dynamo with shunt windings only.

Compounding is resorted to for various purposes. In small lighting installations it is desired to maintain the voltage as uniform as possible without the necessity for an attendant to be constantly regulating the field when variations in load occur.

In such cases the variation in voltage from no-load to full-load should be as small as possible, and the windings should be proportioned so as to fulfil this condition.

In large lighting central stations, where large units are employed, and variations in load may be very great, it is usual to employ shunt dynamos and to regulate the voltage by hand.

In traction central stations the variations in the load are so rapid that it would be almost impossible to regulate the voltage efficiently by hand. Also, it is less important that the voltage should be kept at exactly the same value. Hence, for traction work, compound machines are usually employed, since they automatically adjust their voltage to an approximately uniform value however suddenly the load may vary.

Overcompounding.—In some cases it is necessary to maintain a constant voltage at some point at a distance from the dynamo, and not at the terminals of the dynamo itself. In such a case the dynamo will be required to give an increased voltage at high loads in order to make good the loss of voltage which will occur in the conductors. For example, it is desired to maintain a constant voltage at a certain point in a distribution network. The resistance of the feeders connecting the generator to this point is 0·1 ohm. The loss in the feeders when the dynamo is supplying 100 amperes is $100 \times \cdot 1 = 10$ volts, and consequently the dynamo must give 10 volts more pressure at 100 amperes than when working at no load. A compound-wound dynamo in which the series winding produces an increased voltage at higher loads is said to be *over-compounded*.

The characteristic of such a dynamo should be approximately a straight line inclined upwards at such an angle that the increase in voltage at any point upon it is equal to the product of the current corresponding to that point multiplied by the resistance of the conductor, at the far end of which the voltage is to be kept constant.

Thus at any point increase of voltage = current × resistance of feeder.

Consequently, when designing a winding to maintain a constant voltage through a given resistance, the slope of the characteristic must satisfy the condition

$$\frac{\text{increase of voltage}}{\text{current}} = \text{given resistance.}$$

The points satisfying this condition will lie on the sloping line which the characteristic must approximate to.

If the characteristic curve is drawn so that voltage and current are measured on the same scale the fraction

$$\frac{\text{increase of voltage}}{\text{current}}$$

will be the tangent of the angle which the line satisfying the above condition makes with the horizontal. In this case the characteristic should satisfy the condition

$$\text{Resistance} = \tan \alpha$$

where a is the angle which the characteristic makes with the horizontal.

Long and Short Shunts.—There are two methods of connecting the series and shunt windings of a compound dynamo.

A *long shunt* dynamo has the shunt windings connected in parallel with the armature and series windings. In a *short shunt* machine the shunt is in parallel with the armature alone.

In Fig. 33 the connections are shown for a "long shunt" and "short shunt" dynamo respectively.

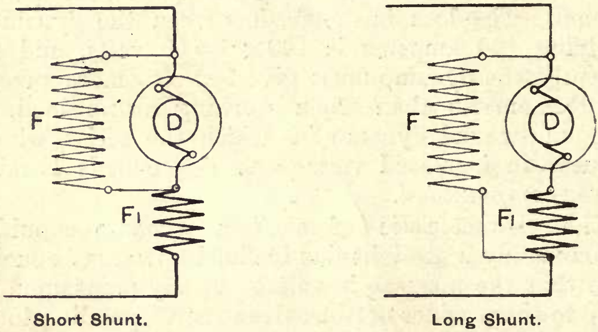


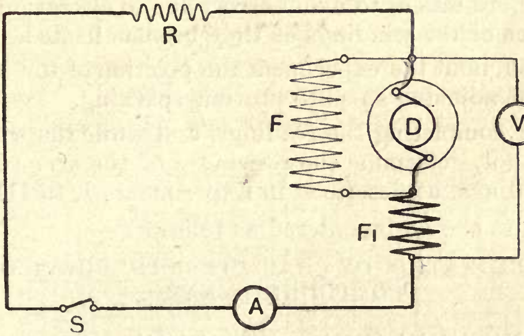
FIG. 33.—LONG AND SHORT SHUNT COMPOUND DYNAMOS.

The difference between the two methods is very slight. The voltage at the ends of the shunt winding will be slightly higher at full load if connected directly to the armature, and hence the excitation will be slightly more. A given machine will therefore give rather more voltage at heavy loads as a "short shunt" than as a "long shunt." This fact is sometimes useful as a means of slightly raising or lowering voltage of a machine if the relation between the windings does not give exactly the desired voltage regulation. By converting a long shunt into a short shunt the voltage at heavy loads is raised, and vice versâ. In conditions frequently occurring in practice the shunt winding would be excited from bus-bars on the main switchboard maintained practically at a constant voltage. The dynamo might then supply current to the same bus-bars, or might be connected to an independent feeder circuit, so that the shunt excitation would be independent of variations of the dynamo voltage.

Characteristic Curve of a Compound Dynamo.—The determination of the characteristic curve for a compound dynamo is very similar to that already described for a shunt dynamo.

Experiment XII.—DETERMINATION OF THE CHARACTERISTIC CURVE OF A COMPOUND-WOUND DYNAMO.

DIAGRAM OF CONNECTIONS.



* FIG. 34.—DIAGRAM OF CONNECTIONS FOR TAKING COMPOUND CHARACTERISTIC.

D	Dynamo armature.
F	Dynamo field shunt windings.
F_1	Dynamo field series windings.
R	Adjustable resistance for varying the load.
A	Ammeter for measuring load current.
V	Voltmeter for measuring dynamo voltage.
S	Switch for breaking main circuit.

Connections.—See that the shunt winding is connected to both brushes of the dynamo, and the series winding to one brush and in series with the load circuit.

Connect the other brush and the free end of the series winding to a variable resistance, including in the circuit an ammeter and switch. Connect a voltmeter to the dynamo terminals.

Instructions.—Take the first reading with the switch S open, and the load nil.

Increase the load gradually by closing the switch and decreasing the resistance R.

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* The dynamo is shown here connected in "short-shunt." For the alternative method of connecting see Fig. 33.

For each value of the load regulate the speed to its normal value, then read the ammeter A, and voltmeter V. Small variations in speed may be corrected for by assuming the voltage and speed to vary in the same ratio, as described in detail on page 59. Then take a similar series of readings while decreasing the load.

The machine should be run for some time before readings are taken, to avoid errors due to alteration in the resistance of the windings as they become heated.

Throughout the experiment the position of the brushes should be adjusted so as to prevent sparking.

After completing the readings, and while the windings are still hot, determine the resistance of the armature and field windings, as described in Experiments I. to III.

Results should be entered as follows :—

DETERMINATION OF CHARACTERISTIC CURVE OF A COMPOUND DYNAMO.

Observer .... Date..............................
Dynamo No. .... Type..............................
Normal output..........volts........amps., at........revs. per min.
Resistance of armature (hot) ....ohms.
Resistance of shunt field windings (hot)............ohms.
Resistance of series field windings (hot)............ohms.

Load Current.		Revolutions per Minute.	Voltage.	
Ammeter No. .... Constant			Voltmeter No. .... Constant	
Reading.	True Value.		Reading.	True Value.

Plot a curve showing the dependence of voltage upon load, plotting current horizontally and voltage vertically.

The curve drawn as a full line in Fig. 35 is given as an example of a characteristic obtained from a short shunt $2\frac{1}{2}$ kw. compound-wound dynamo. The curve slopes upwards at first, since the magnets are unsaturated, and, consequently, the permeability of the iron circuit is high. The increase in exciting current in the series coils produces a relatively large increase in the strength of field. As the fields become saturated, the permeability falls, and an increase in magnetising force produces a smaller effect. The losses of voltage due to armature reactions are, consequently, not entirely counterbalanced by the increase of excitation, and the curve gradually falls again. It is usual to adjust the windings so that the machine gives its normal voltage at "no load" and "full load." It will then give a slightly higher voltage between these limits, and a lower voltage above full load.

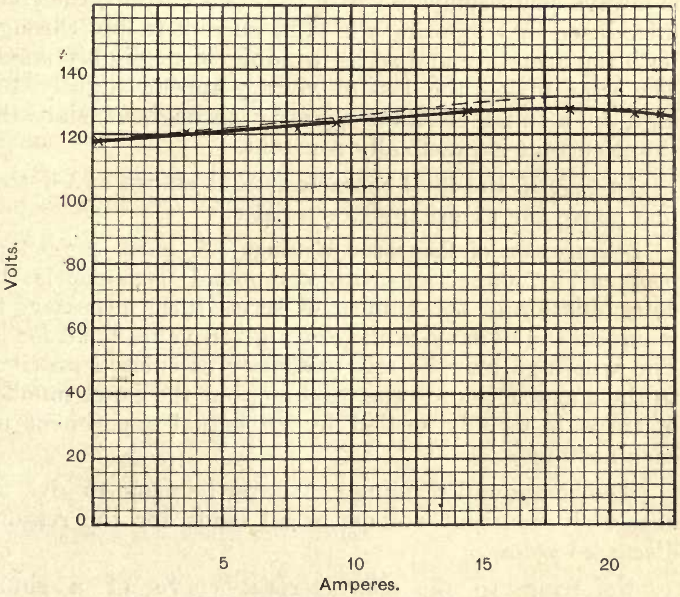

FIG. 35.—CHARACTERISTIC OF COMPOUND DYNAMO.

In order to obtain the minimum variation from the normal voltage, the no-load and full-load voltage must be taken slightly below the normal.

Total Characteristic.—The method of obtaining the total, or internal, characteristic from the experimentally-obtained external characteristic curve, is a combination of the methods already described in the case of the shunt and series characteristics, since current will be spent in the shunt field winding, and voltage will be lost in the series coils and armature conductors.

In the case of a compound dynamo connected in long shunt, the construction given on page 76 for obtaining the total characteristic of a shunt dynamo may be followed exactly, except that, instead of the armature resistance, the resistance of the armature and series winding together must be substituted in every case.

If the machine is connected in short shunt the armature current will be the sum of the exciting current and the main current, while the current in the series field winding is the main current only. As the shunt current is always small compared with the main current, the error introduced by supposing the same current to flow through both the armature and series winding is negligibly small. The error makes the loss of voltage appear slightly too high by a small constant quantity throughout, since the shunt current is practically constant.

In Fig. 35 the total characteristic is shown as a dotted line above the external characteristic.

Determination of Compound Windings.—A most important problem in connection with compound dynamos is the determination of the number of series turns necessary to maintain the dynamo voltage at a given value at all loads. The windings may be approximately calculated previous to the construction of the machine, but the exact number of turns is usually settled by an actual experiment on each machine.

The compound winding can never be made to give an absolutely constant voltage at all loads for the reasons discussed below.

Referring to the characteristic curve of a shunt dynamo, Fig. 23, page 72, it will be seen that the first part of the curve is a fairly straight line sloping downwards. Later on the curve drops more decidedly. In order to maintain the voltage constant, the series winding must therefore strengthen the field by a uniformly increasing amount at first, and by a more rapidly increasing amount as the load increases further. The magneto-motive force of the series winding, however, is always proportional to the current flowing in it, *i.e.*, proportional to the load of the dynamo. If the increase in the strength of field can be made to be proportional to the increase in magneto-motive force, then, by choosing the right number of series turns, the dynamo voltage can be kept constant for such variations of load as occur within the straight portion of the shunt characteristic curve. Within this limit the armature reactions produce a fall of voltage approximately proportional to the load, and the reinforcement of the field by the series coil will also be proportional to the load.

In order that the increase in field strength shall be proportional to the magneto-motive force of the series winding, the magnetic density in the circuit of the machine should be so chosen that the shunt winding alone is sufficient to carry the magnetisation just over the bend (see Fig. 10, page 32). The effect of the series coils will then produce a strengthening of the field approximately proportional to the amount of current flowing in them.

$\frac{156}{2.1}$

At the point where the shunt characteristic falls below the straight line forming its first part, the fall of voltage due to armature reaction increases at a greater rate than the load, and, since the series excitation only increases in proportion to the load current, there will be a fall of the terminal volts.

Since it is usually necessary to limit the fall of voltage at full load to a fixed amount, it becomes frequently necessary to employ more series turns than are sufficient to maintain the voltage constant at light loads. The characteristic, therefore, rises at first, and then becomes level for a time, and finally tends downwards as the load approaches its maximum value.

Calculation of Series Winding.—Having obtained the magnetisation curve and characteristic of a shunt-wound or separately excited dynamo, it is a very simple matter to calculate the number of series windings required to keep the voltage at any given value at any given load.

$\frac{154}{92}$

An example in connection with curves given above will serve to make the method of procedure clear.

The curve shown in Fig. 14, page 51, shows the fall of voltage produced by armature reactions in a dynamo excited from a source of constant electromotive force.

Let it be desired to determine the number of series turns which must be added to the field of the machine in order to make the voltage at 20 amperes the same as is no load.

Let Fig. 12, page 39, be the magnetisation curve determined for the same machine.

With a load of 20 amperes at constant excitation the loss of voltage is 16 volts (see Fig. 14).

From the magnetisation curve(Fig. 12) it is seen that the exciting current corresponding to the no load voltage of 120·5 is 1·07 amperes. This corresponds to 2,800 × 1·07 ampere turns = 2,996 ampere turns. In order to increase the voltage by 16 volts it would be necessary (see Fig.12) to increase the exciting current to 1·425 amperes, producing a magnetising force of 3,990 ampere turns—an increase of 994 ampere turns. This increase in ampere-turns must be produced by a current of 20 amperes in the series winding, which must consequently have $\frac{994}{20} = 50$ turns.

The results of such a calculation based upon curves taken on any particular machine should give sufficiently accurate results. Where tests of the machine have not been previously made, or when the results of experiments made on a single machine are taken as applying to a number of similar machines, the final adjustment of the number of windings is made after trial of the machine. A few extra series windings are wound on to the magnets, and the superfluous ones are removed as found necessary after the machine has been run up to full load, until the voltage is brought down to the required value.

Another practice adopted in some shops is to wind the machine only with the shunt coils at first, and during the test to wrap a number of turns of insulated cable roughly round the magnets, to serve as a temporary series winding. This winding may be supplied with the current of the machine itself, or from a separate source, such as an accumulator battery. The number of coils required to make the dynamo give its required voltage is thus found by trial, the permanent winding being added afterwards in place of the temporary coils of cable.

Another method of obtaining the correct number of series windings to maintain a constant voltage is to make use of results obtained, as in Experiment VII. (page 62). The required number of turns may be taken from the results of this experiment as plotted in Fig. 18 (page 64).

In order to determine the number of series windings necessary to enable the machine to give the same voltage at full load as at no load, take from the curve (Fig. 18) the number of ampere-turns required at full load to maintain the required voltage. Subtract from this number the ampere-turns at no load. The difference gives the ampere-turns to be supplied by the series winding. Dividing this number of ampere-turns by the current, we obtain the number of turns required.

The method of calculation from the characteristic of the separately excited machine (Fig. 14) will be readily followed from the example given above.

CHAPTER VIII.

EFFECT OF CURRENT IN THE MOTOR ARMATURE.

Cause of Rotation of the Armature.—When current is sent through the armature of a 2-pole motor from the positive to the negative brush, it divides and flows along the two parallel circuits formed by the conductors on each side of the armature. The effect of these parallel currents is to make the armature act as if magnetised with a north and south pole respectively at the ends of the diameter obtained by joining the conductors connected to the brushes. (See Fig. 36, which should be compared with Fig. 15, page 52, drawn for a dynamo).

With the brushes in their normal position, the magnetic axis of the armature will be perpendicular to the main field of the motor. The North pole formed in the armature will therefore be attracted by the South pole of the field magnets, and tend to produce rotation of the armature. The same action will take place between the South pole of the armature and the North pole of the field. The brushes remain in the same position, and transmit current to conductors situated in the same position, irrespective of the rotation of the armature. The position of the poles formed in the armature, therefore, is always the same relatively to the field, and the rotation is continuous.

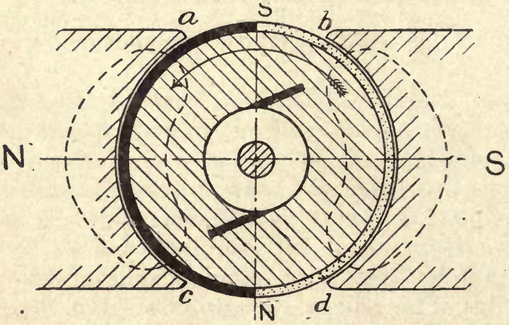

FIG. 36.—DIAGRAM OF ARMATURE CURRENTS IN A MOTOR.*

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* See footnote on page 53.

Torque of a Motor.—Torque is the term usually employed to express the turning effort exerted on the shaft by the motor armature. In British units, torque, or turning moment, is measured in pound-feet, *i.e.*, in terms of a pull of a certain number of pounds exerted at a radius of 1ft. from the centre of the shaft and tending to turn the shaft.

In a motor this effort will be due to the action of the magnetic poles formed in the armature, by the armature current, upon the fixed poles of the motor. The torque is proportional to the product of the strengths of the poles which act upon each other.

In the case of a motor having a constant field, the torque is given by the formula

$$\text{Torque (in lb. ft.)} = \frac{\text{N.F.C.}}{8{\cdot}52 \times 10^8}$$

Where N = number of armature conductors.

F = number of lines of force in the main field.

C = armature current.

For a motor with constant field the torque is proportional to the current, and independent of the speed, since speed does not enter into the expression.

If the field varies (as in a series motor) the torque will increase or decrease in proportion to the variation of the strength of field and of the armature current jointly.

Counter Electromotive Force.—In construction, a motor is similar to a dynamo. It follows that the rotation of its armature in the magnetic field of force of its magnets will produce an electromotive force in the same manner as in a dynamo. The direction of this electromotive force will always be such as to oppose the electromotive force of the source of power producing the rotation. For this reason it is called the counter electromotive force of rotation, or the back electromotive force.

The formula given on page 25 for the electromotive force induced in the armature of a dynamo applies equally in this case.

$$\text{Back electromotive force} = V_B$$
$$= \frac{\text{rate of cutting magnetic lines}}{10^8} = \frac{N.n.F.}{60 \times 10^8 \times p}$$

Where

N=number of conductors on the circumference of the armature.
n=number of revolutions of the armature per minute.
F=number of magnetic lines cut by the conductors.
p=number of pairs of magnet poles in the motor.*

Thus there exist two electromotive forces in the armature of a motor, acting in opposite directions, viz., the electromotive force of the source of supply applied to the motor to produce rotation, and the back electromotive force produced in the motor armature by its rotation.

It is the difference between these electromotive forces which produces the current flowing in the armature. This current is numerically equal in magnitude to the unbalanced electromotive force, divided by the resistance of the armature circuit through which it flows.

Let V = voltage at which current is supplied at the motor terminals.
V_B = back electromotive force generated in the motor armature by its rotation.
R = resistance of the armature measured from terminal to terminal.
C = current flowing through the armature.

Then from what has just been said

$$C = \frac{V - V_B}{R}.$$

The amount of power given to the motor measured in watts is given by the equation† :

$$\text{Watts given to motor} = W = C.V. = V\frac{V - V_B}{R}$$

This is the power spent in overcoming the frictional and other losses in the motor and in doing useful work.

Any decrease in the back electromotive force must produce an increase in the armature current. Similarly an increased back electromotive force is always followed by a decreased armature current.

---

* If the armature of a multipolar motor is series connected and provided with a single pair of brushes, the factor p must be omitted in the formula. See footnote, page 25.

† This leaves out of consideration the small constant current taken by the field windings.

The back electromotive force may be varied in either of two ways, viz., by altering the speed of rotation, or by altering the strength of the field in which the armature rotates. The latter case is considered later under the heading of "Methods of Speed Variation." (See pages 110 and seq.).

A decrease in speed produces a smaller back electromotive force, and, therefore, an increase in the current and power given to the motor. Thus an increase in the load applied to the shaft of the motor automatically produces an increase in the driving power by reducing the speed and back electromotive force of the armature.

The current will heat the armature and produce a waste of power of C^2R watts.

$$\text{Now, } C^2R = C.\frac{V - V_B}{R}.R = C\,(V - V_B)$$

$\therefore$ power wasted in armature conductors $= C\,(V - V_B)$.

Also power supplied to motor $= C\,V$.

$$\text{Hence power spent in driving shaft} = C\,V - C(V - V)$$
$$= C\,V_B$$

That is, the product of current and back electromotive force represents the useful output of the armature.

Also the electrical efficiency of the armature

$$= \frac{\text{useful watts}}{\text{watts supplied}} = \frac{C\,V_B}{C\,V} = \frac{V_B}{V}$$

i.e., the ratio of the back electromotive force to the electromotive force applied to the motor.

Methods of Field Excitation.—As in the case of dynamos, motors may be classified according to the method adopted for supplying current to their field windings.

In a **shunt motor** the exciting circuit and armature circuit are connected in parallel to the supply mains, and the amount of current flowing in the armature and field can be independently regulated, since armature and field are independently supplied.

In a **series motor** the armature and field coils are connected in series with each other to the mains.

The same current therefore flows through both.†

---

† In special cases a variable shunt resistance is provided in parallel with the series winding, by means of which the proportion of the armature current flowing through the magnet windings may be varied. Some of the armature current can be made to flow through the shunt resistance instead of the magnet coils. In other cases the number of coils in circuit is made to vary, so that the strength of field produced by a given current may be controlled.

Compound Motors have both series and shunt windings on their magnets, so that the excitation is partly constant and due to the supply voltage, and partly depends upon the armature current.

Starting Switch.—As just explained, the amount of current taken by a motor depends upon the back electromotive force produced in its armature. The back electromotive force is proportional to the speed of rotation, and will be zero when the motor starts from rest. If the armature of a stationary motor were connected directly to the supply mains the strength of the armature current would be exceedingly high, and would be quite high enough to injure the armature insulation.‡

It is, therefore, invariably the practice to start motors from rest by means of a special starting switch, which is so arranged that on starting, the armature is first connected to the supply source through a resistance sufficiently high to reduce the current to a safe value. By moving the switch handle slowly through several positions the resistance in series with the armature is gradually diminished as the motor speed, and the back electromotive force of the armature increase. In the final, or running, position of the switch the resistance is entirely cut out, so that the armature current then depends on the back electromotive force of the motor alone.

In the case of a shunt motor it is essential that the magnets should always be excited when the armature receives current, in order that they may act upon the armature and produce rotation. This is usually accomplished by the addition of a sector to the switch, as shown on Fig. 37, where the connections between the switch and motor are also indicated. In the position shown on the diagram the switch is "off," and no current passing. When moved round, the switch first completes the circuit through the motor field winding, and the resistances r_1, r_2 made of fine wire§. The next positions of the handle cut out these resistances and connect the motor field winding direct to the supply mains.

---

‡ For example, a 40 h.p. shunt wound motor had an armature resistance of ·0167 ohm. When working at full load the current in the armature was 300 amperes at 110 volts. If connected directly to the mains in order to start the motor from rest, the current at starting would have been $\frac{110}{\cdot 0167} =$ 6,600 amperes. This is 22 times the full load current for which the motor was designed. The maximum current should not exceed twice the normal full load current for fear of injury to the armature insulation. For starting the above motor a resistance of ·2 ohm was inserted in the circuit by the starting switch. The maximum starting current was therefore $\frac{110}{\cdot 2167} =$ 500 amperes approximately.

After this the armature is connected to the mains through the resistances r_3, r_4, r_5, r_6, r_7. These resistances are successively cut out, until when the switch handle is in the extreme position to the right, both armature and field are connected directly to the supply mains.

The switch handle should be moved "on" slowly to allow the motor to gather speed between each position. It should be moved "off" quickly, so as to break the current while the motor speed is still high and the armature current low.

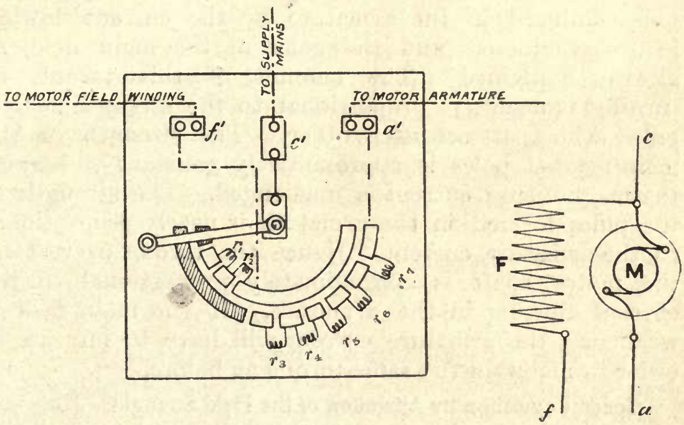

FIG. 37.—MOTOR STARTING SWITCH.

The starting resistance has three terminals. (See Fig. 37.)

f', connected to the field sector;

a', connected to the end of the armature circuit resistance;

c', connected to the switch lever.

In a shunt motor one end of the field winding remains permanently connected to one of the brushes. The motor has then three free terminals.

---

§ The purpose of these resistances is to lessen the strong rush of current which occurs when making or breaking the field circuit on account of its high self-induction. These resistances are omitted in small motor-starting switches.

a connected to one of the brushes,
f connected to the shunt winding,
c connected to the other brush and the shunt winding.

When connecting up a motor to the mains through a starting switch, join *f′* to *f*; also *a′* to *a* (with a stouter wire), and then connect the terminals *c*, *c′*, of the switch and motor to the mains. A common mistake with inexperienced or careless operators is to interchange the connections to *a′* and *c′* on the starting switch; this weakens the field at starting, and causes the motor to start at a high speed, the current becoming excessive as the resistance is cut out by moving the switch handle.

Motor Speed Regulation.—The force tending to turn the shaft of a motor is due to the attraction between the poles induced in the armature by the current flowing in its conductors and the poles of the main field, as already explained The amount of this torque, or turning moment, is proportional to the strength of the poles which attract each other. The strength of the main magnet poles is approximately constant so long as the magnetising current is unchanged. The strength of the poles formed in the armature is nearly proportional to the armature current. Hence the torque exerted by the motor shaft is approximately proportional to the current flowing in the armature. If the main field is weakened, the armature current will have to increase in order to maintain the same torque as before.

Speed Regulation by Alteration of the Field Strength.—Suppose a motor to run with a constant load applied to its shaft, and constant voltage applied at its terminals. The motor will run at constant speed, the current in the armature being just sufficient to react on the magnetic field with the force necessary to overcome the resistance to turning due to the load on the shaft, friction in the bearings, &c.

If the field strength were lessened, the back electromotive force would decrease in the same proportion, if the speed of rotation remained as before. This would allow a stronger current to flow through the armature, *i.e.*, the motor would receive more power. The increased power supplied to the motor would make it run faster, until the back electromotive force had again increased to such a value that the power taken by the motor was that needed to enable it to overcome the resistance of the load at the new speed. Under the new conditions the attraction between armature poles and main field poles will again just balance the resistance to turning due to friction and the load on the shaft.

Thus, a *decrease* in excitation produces an *increase* in speed.

The regulation of a shunt motor may be easily accomplished by connecting a variable resistance in series with the shunt magnet winding. The current in the shunt winding is small, and therefore the waste of power in such a resistance is not great.

In a series motor the whole of the armature current circulates in the magnet winding. The field regulation in this case is more economically carried out by putting a variable resistance in a branch circuit in parallel with the magnet winding. The current round the magnets is then decreased by decreasing the variable resistance in the parallel branch circuit, causing more current to pass through the resistance, instead of through the field windings.

The number of magnet windings may also be decreased in order to weaken the field strength. This is in general not so easy to carry out.

The method of speed regulation by varying the field is illustrated in the case of a shunt motor by the next experiment. (For diagram of connections, see page 112.)

Experiment XIII.—DETERMINATION OF VARIATION IN SPEED OF A MOTOR, WITH ITS EXCITATION.

Connections.—Connect the motor to the source of supply through a starting switch. (See page 109). If necessary to maintain the voltage at the correct value, insert a variable resistance between the switch and the motor terminal. Put a variable resistance and an ammeter in series between the field terminal of the motor and its connection to the starting switch.

Connect a voltmeter to the armature terminals.

Instructions.—Keep the voltage at the armature terminals constant throughout the experiment by varying the resistance R_1 when necessary.

Beginning with the resistance R_2, entirely cut out, increase its value gradually.

For each value of the exciting current take readings of exciting current, speed, and armature voltage (which should remain constant).

The motor should be unloaded or else made to exert a constant torque.

Two sets of readings should be taken, with increasing and decreasing field currents, respectively.

DIAGRAM OF CONNECTIONS.

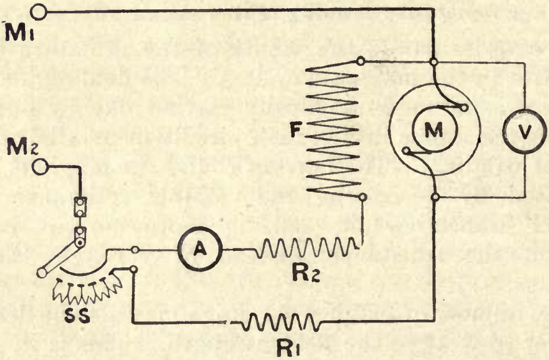

FIG. 38.—VARIATION IN SPEED OF MOTOR WITH EXCITATION.

M_1 M_2	Supply mains.
M	Motor armature.
F	Motor field windings.
R_1	Adjustable resistance for regulating voltage at armature terminals.
R_2	Adjustable resistance for varying exciting current.
V	Voltmeter for measuring voltage across armature.
A	Ammeter for measuring exciting current.
SS	Starting switch.

Plot a curve showing dependence of number of revolutions per minute upon exciting current.

Fig. 39 shows such a curve obtained from a small 2-pole shunt-wound motor in this way.

The readings should be entered as on the following table :—

DETERMINATION OF DEPENDENCE OF SPEED OF A SHUNT MOTOR UPON EXCITATION.

Observer .... Date ....
Motor No. .... Type ....
Normal output............h.p., at............volts, and.........revs. per min.

Exciting Current.		Revolutions per Minute.	Armature Voltage.	
Ammeter No. .... Constant........................			Voltmeter No. .... Constant........................	
Reading.	True Value.		Reading.	True Value.

The curve resulting from this experiment may be considered to be practically a magnetisation curve for the motor. The power necessary to drive a motor when running light should be very small. Consequently the back electromotive force will remain practically constant (since the difference between the applied electromotive

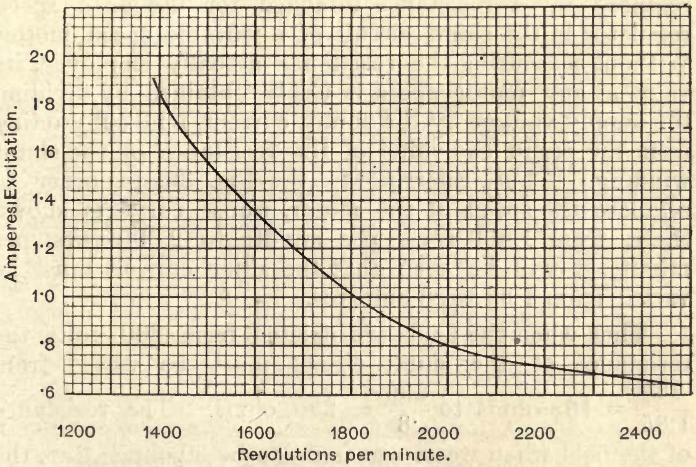

FIG. 39.—DEPENDENCE OF SPEED OF MOTOR UPON EXCITATION.

force and the back electromotive force determines the power absorbed), and the speed will have to increase approximately in the same ratio as the strength of field decreases, in order to maintain the back electromotive force at the same value.

Thus the speed will be approximately inversely proportional to the strength of the field, and the curve shows the relation between exciting current and strength of field. The shape of the curve may therefore be used to determine the point in the "saturation curve" at which the motor magnetic circuit is being excited.

By turning the curve up on end, so that the speed line becomes vertical, and the highest speed is at the bottom of the curve, the resemblance to the magnetic curves already obtained becomes apparent.

A motor having a small air gap would give a curve with a much sharper bend than that shown in Fig. 39, which was taken from a 3 h.p., smooth core, 2-pole Crompton motor.

A further result obtained from the experiment is a determination of the magnitude and degree of regulation required by a resistance intended for use as a speed regulator in the shunt circuit of a variable speed motor. Without measuring the resistance actually employed, its value at any motor speed is easily obtained by dividing the supply voltage by the shunt current, and subtracting from the result the value of the resistance of the shunt winding. Thus, referring to the Fig. 39, in order to regulate the speed of the motor, whose curve is shown there, from 1,400 revs. per minute to 2,000 revs. per minute, it will be seen that the shunt current must be varied from 1·85 to ·8 amperes.

Thus when the fields are excited from 200 volts, the resistance of the shunt circuit must be varied from $\frac{200}{1{\cdot}85} = 108$ ohms to $\frac{200}{{\cdot}8} = 250$ ohms. The resistance of the field when warm was found to be 80 ohms; thus the regulating resistance for the two speeds would be 28 and 170 ohms respectively.

In this calculation the load is assumed to remain unchanged. If the load varies considerably, the variation in speed due to the change of load must be allowed for in calculating the variation of excitation necessary. This variation is, however, never very great in the case of a shunt motor working at ordinary loads.

The results of the experiment may also be plotted in such a way as to compare directly speed and resistance, the resistance being calculated each time from readings of the exciting current and voltage of supply.

Obviously the increase in resistance of the field windings of a motor, due to their becoming heated by the current, will affect the speed of the motor. After starting with the windings cold, the motor will gradually increase its speed as they become heated.

The method of regulating the speed by varying the excitation is also applicable to series motors. In this case the field current is varied by connecting a variable resistance in parallel with the field coils.

The preceding experiment cannot be readily carried out with an unloaded series motor, as the speed of a series motor when unloaded becomes dangerously high; but it may be carried out almost exactly as described with the motor shaft connected to a constant load.

In this case *decrease of resistance* will correspond to *decrease of strength of field and increase of speed.*

Regulation of the Speed of a Motor by a Resistance in the Armature Circuit.—This method practically operates upon the motor by varying the voltage at the armature terminals, since the function of the resistance is to absorb a certain portion of the voltage of the mains, and thus to reduce the voltage applied to the motor armature

The voltage at the armature terminals is most readily varied by putting a resistance in the armature circuit to absorb a portion of the voltage of the mains supplying the motor, although any other method of producing the effect will have the same result—*e.g.*, putting two motors in series, so that each may absorb part of the main voltage, or connecting them to mains at different voltages.

The use of a resistance in the armature circuit for purposes of regulation is generally very wasteful, since the whole armature current passes through and heats the resistance. It is, however, frequently useful to employ a series resistance for varying the speed during short periods or for special purposes. The same switch and resistance frame as are employed in starting the motor (see page 108) are convenient for the purpose, if fine variations of speed are not required.

It should be noted that the resistances intended for use with a starting switch are not always made of sufficiently stout wire to permit of their being left in the circuit for lengthy periods. In starting a motor they are used for such a short time that they have not time to get overheated. When the motor is heavily loaded, its current is high, and the heating effect of the current is therefore increased, and may exceed the carrying capacity of the resistance.

In comparing this method of regulating the speed with the method by field regulation, it should be remembered that the current in the armature varies with the load on the motor. The voltage absorbed by a resistance in series with the armature will also vary with the load, since the drop is the product of the resistance (in ohms) by the current (in amperes) flowing in it. Thus an increase in load will at once affect the voltage applied to the armature and will consequently affect the speed in a two-fold manner. If the regulating resistance is in the shunt winding, on the other hand, its effect upon the speed of the motor will be unaffected by variations in the load.

Experiment XIV.—Determination of the Relation between Speed and Voltage of a Motor having Constant Excitation.

Diagram of Connections.

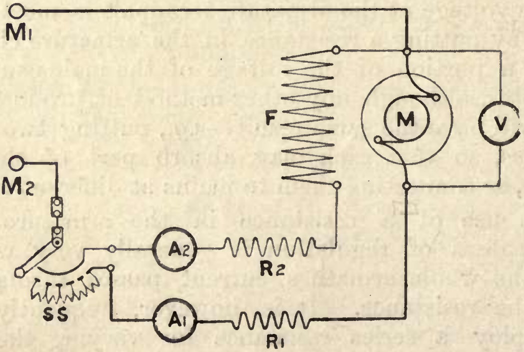

Fig. 40.

M_1 M_2	Supply mains.
M	Motor armature.
F	Motor field windings.
R_1	Adjustable resistance for varying voltage at armature terminals.
R_2	Adjustable resistance for regulating exciting current.
*A_1	Ammeter for measuring armature current.
A_2	Ammeter for measuring exciting current.
V	Voltmeter for measuring volts across armature.
SS	Starting switch.

Connections.—Connect the motor to the mains through a starting switch. Put a variable resistance in the armature circuit, and an ammeter and adjustable resistance in the field circuit. Connect a voltmeter to the motor terminals.

Instructions.—Keep the exciting current constant throughout the experiment by varying the resistance R_2 when necessary.

Beginning with the resistance R_1, entirely cut out, increase its value gradually, so as to decrease the voltage at the motor terminals. For each value of the voltage observed upon voltmeter V, take readings of the speed of the armature, and of the exciting current. Although not strictly part of the experiment, readings of the armature current should be taken also.

Plot a curve showing dependence of number of revolutions per minute upon armature terminal voltage.

Fig. 41 shows a curve resulting from this experiment. The curve consists of a straight line passing through zero. This shows that the speed is proportional to the voltage applied to the motor armature when the excitation is maintained constant.†

---

* This is not necessary for the experiment.

† This is *practically*, but not *rigidly* true. The *back electromotive force* of the motor is strictly proportional to the speed with constant excitation. The back electromotive force is always less than the electromotive force applied at the terminals by an amount equal to the product of the armature current and the resistance between the motor terminals. The current taken by the armature increases with the speed, but not in proportion to the speed. Hence it follows that the difference between the applied electromotive force and the back electromotive force does not increase in the same proportion as the speed of the motor, and the applied electromotive force must increase at a slightly higher rate than the speed. At no load the difference between the applied and back electromotive forces is so small that this lack of proportionality can be neglected in the case of a fairly efficient motor.

Readings should be entered as follows:—

DETERMINATION OF DEPENDENCE OF SPEED OF A MOTOR UPON ITS VOLTAGE.

Observer.................................. Date...
Motor No. .... Type..
Normal output. ...........H.P., at.........volts, and.........revs. per min.
Exciting current..................Amps.

Armature Voltage.		Revolutions per Minute.	Exciting Current.		Armature Current.	
Voltmeter No. ...... Constant			Ammeter No.... Constant		Ammeter No....... Constant	
Reading.	True Value.		Reading.	True Value.	Reading.	True Value.

This experiment is really the converse of Experiment IV., in which it was found that the voltage of a uniformly-excited dynamo was proportional to the speed.

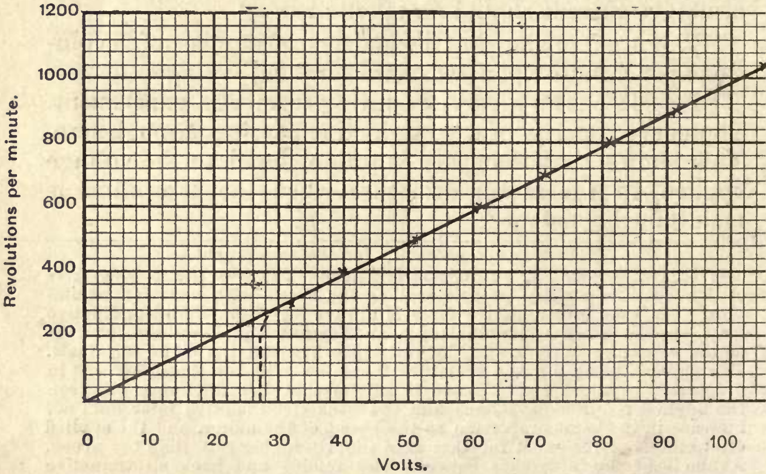

FIG. 41.—DEPENDENCE OF SPEED OF A MOTOR UPON ARMATURE VOLTAGE. EXCITING CURRENT CONSTANT = 1·5 AMPERES.

As in the case of the dynamo, the inclination of the line, showing the result of the experiment, will be different for each value of the excitation.

In carrying out the experiment it will be found impossible to get points on the curve corresponding to very low speeds. The motor will not run steadily at very low speeds.

Thus, in Fig. 41 the lowest reading actually taken was for a speed of 295 revs. per minute. The motor could not be got to run at less than 255 revs. per minute. The curve representing *observations* should, therefore, strictly speaking, follow the dotted line shown on the figure.

With constant loads on the shaft, other curves may be obtained which will also be *approximately* straight lines, the angles which they make with the horizontal depending on the load. As the current corresponding to each load is constant, the effect of armature resistance, &c., will be greater for higher loads, and the lines will consequently tend to bend over in the case of heavy loads on the shaft.

It is advisable in both this and the preceding experiment to insert an ammeter in the armature circuit (as shown in Fig. 40), and to observe the variation in the armature current in the two cases.

When the field is variable and the load is constant (Experiment XIII.) the armature current increases as the field strength decreases, so that a constant torque may be maintained.

Where the field and load are both constant (Experiment XIV.), the armature current only varies very slightly to make up for variation in friction and other losses. In either case current and speed are practically independent of each other.

Two very important conclusions are to be drawn from the results of the preceding experiment and discussion, applying to a motor having constant excitation.

(1) For any given speed there is a definite back electromotive force induced in the armature, independent of load or voltage applied.

(2) For a given load on the shaft the armature current will have a definite value, independent of speed and voltage.

The speed of the motor adjusts itself automatically, so that the applied electromotive force, acting in opposition to the back electromotive force corresponding to the speed, is just sufficient to send this current through the armature.

These conclusions make it possible to determine beforehand the voltage necessary to make a motor run at any other speed than the usual one.

Also the magnitude of a starting or regulating resistance to be used in connection with a motor can be calculated when the current taken by the machine at any speed is known.

A similar experiment may be carried out for a series motor. In this case the resistance, R_1, which varies the armature voltage, will be in series with the field windings as well as the armature.

For a given load (as explained above), the current must remain at a constant value in both armature and field, irrespective of the speed of the motor, since the torque due to the load requires that armature and field poles should have a definite mutual attraction.

When the motor is running light, the effect of introducing a resistance in series with the motor circuit will be to reduce the voltage at the motor terminals without reducing the current. In order that the same current may continue to flow, and the armature exert the same torque, with a decreased voltage at the terminals, the counter electromotive force of the armature must be reduced by a reduction of speed, proportional to the reduction of counter electromotive force necessary to maintain the original current.

Thus for a series motor running light, the curve comparing speed and voltage will be approximately a straight line, as in the case of a shunt motor.

The same will be true for a series motor running at constant load (*i.e.*, with a constant resistance to turning at the shaft), except that, as the current will be greater, the effects of armature resistance, hysteresis, eddy currents, and air friction may affect the curve sufficiently to cause it to bend over.

The curves in Fig. 42 were obtained by applying a brake to a 9½in. pulley on the shaft of a small series wound motor, whose armature and field resistances were low. The pull on the brake was maintained constant for the readings recorded in each curve. It will be seen that for a fairly wide range of speeds the variation of speed and electromotive force remained so nearly proportional that the curves appear as straight lines.

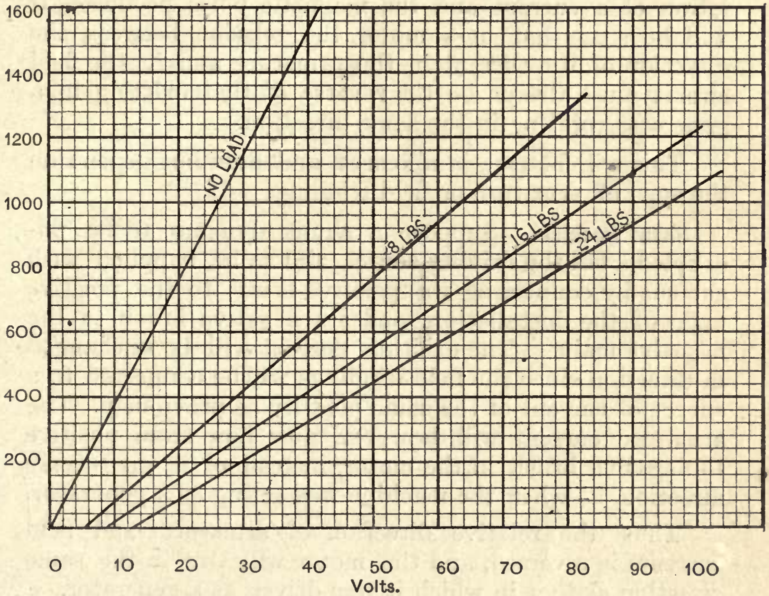

FIG. 42.—VARIATION IN SPEED OF SERIES MOTOR AT DIFFERENT VOLTAGES AND LOADS.

The amount of the pull applied through the brake to the pulley in each case is stated on the respective curves.

The effect of armature resistance, and of other losses increasing with the current, makes the three right-hand curves cut the horizontal axis some distance from O.

A means of lessening the excessive speed of a series motor at light loads, is to employ very strongly-saturated fields. The decrease of current at light loads has in such cases a smaller weakening effect upon the field, and consequently the speed of the motor rises less rapidly. Thus at the lightest load contemplated, the induction in the fields must still be sufficiently strong to correspond to the flat branch above the "knee" of the magnetisation curve. This increases the number of ampere-turns required, and consequently both the initial cost and the power spent in excitation.

Relation Between Direction of Rotation of Dynamo and Motor.—Comparing Fig. 15 (page 52) and Fig. 36 (page 104), and recalling the connection between the direction of circulation of a current and the magnetic poles produced, it will be seen that in a motor the relation between the direction of the current in the armature and in the field circuit must always be the reverse of that existing in a generator rotating in the same direction.

This will be true in all cases, and does not depend on the type of armature or field winding.

Shunt Machines.—Suppose a shunt dynamo to be uncoupled from the driving source and to be supplied with current by connecting its positive brush to the positive main of the installation, and its negative brush to the negative main. The exciting current will be unchanged in direction since the field windings will be connected to a source of current of the same polarity as previously. The armature current will, however, now flow from positive to negative brush in the motor, instead of in the reverse direction, as when the machine was acting as a generator.

Thus the relative direction of armature and field currents is reversed, and the motor will run in the same direction as that in which it was driven as a generator.

A shunt machine will according run in the same direction if connected to a circuit, whether it is supplying current to the circuit as a generator, or whether it is taking current from the circuit and working as a motor.

Critical Speed.—If the machine is driven at such a speed that its voltage exceeds that of the line to which it is connected, it will supply current to the line.

If the speed is less, so that the machine voltage is lower than the line voltage, the machine will receive current and be driven as a motor.

At a definite intermediate speed the two voltages of the machine and of the line will be exactly equal, and the machine will neither receive nor give out current. This speed is known as the *critical speed* of the machine. If running below the critical speed, the machine is a motor. When driven at a speed higher than the critical speed, the machine becomes a generator.

Series Machine.—If a series dynamo be allowed to receive current from the line which it has been supplying, the direction of the current in both armature and field will be reversed. The *relative* direction of armature and field current is therefore unchanged. Consequently the machine cannot continue to rotate in the same direction, but will be driven as a motor in the *opposite* direction to that in which it rotated as a generator.

Since a series machine rotates in opposite directions when acting as motor and generator, it cannot be said to have a "critical speed" in the same way as a shunt machine.

CHAPTER X.

EFFICIENCY TESTS OF A MOTOR.

Efficiency of a Motor.—The efficiency of an electromotor is the ratio of the mechanical power exerted by the motor to the electrical power supplied to it.

Expressed as a percentage

$$\text{Efficiency per cent.} = \frac{\text{power exerted}}{\text{power received}} \times 100.$$

In the above ratio both amounts of power must be expressed in terms of the same unit.

Electrical power supplied to the motor is measured in watts. The number of watts supplied is numerically equal to the product of the current (in amperes) multiplied by the pressure (in volts) measured at the motor terminals.

Mechanical output is usually measured in terms of horse-power, and is termed the brake horse-power, or B.H.P., of the motor. One horse-power is equivalent to an output of 33,000 ft.-lbs. per minute, or to 746 watts.

To express both input and output in terms of the same unit, it is usual to express both in horse-power.

Dividing the watts supplied to the motor by 746 the input is obtained in horse-power, usually called the electrical horse-power, or E.H.P.

We may write

Efficiency of motor per cent.

$$= \frac{\text{B.H.P. output}}{\text{E.H.P. input}} \times 100$$

$$= \frac{\text{B.H.P.}}{\text{amperes} \times \text{volts}} \times 74{,}600.$$

Brake Tests.—In testing a motor, the mechanical output, or brake horse-power, is most simply measured by applying a friction brake to the rim of a pulley on the motor shaft, and measuring the retarding force exerted by the brake on the pulley.

Power is the rate at which a force is exerted or overcome in a given direction.

In the case of a brake applied to a rotating pulley, the force is the retarding force exerted at the surface of the pulley, due to the friction between the brake and pulley. The rate at which this force is overcome in a direction tangential to the pulley is the speed with which the rim of the pulley moves relatively to the brake.

Let p be the force in pounds exerted by the brake at the rim of the pulley.
d the diameter of the pulley in feet.*
n the number of revolutions of the pulley per minute.

Then the horse-power exerted by the motor is

$$\text{B.H.P.} = \frac{\text{Number of ft.-lbs. per min.}}{33{,}000}$$

$$= \frac{\text{lbs. pull} \times \text{speed of pulley rim}}{33{,}000} = \frac{p \times \pi\, n.d.}{33{,}000}$$

Hence efficiency of motor per cent.

$$= \frac{\pi\, p.n.d.}{\text{amperes} \times \text{volts}} \times \frac{74{,}600}{33{,}000}$$

The quantity $\frac{74{,}600}{33{,}000}\,\pi\, d$ will be a constant number for any particular brake pulley. Writing k instead of this expression,

$$\text{Efficiency of motor per cent.} = k\,\frac{p\,n}{\text{amperes} \times \text{volts.}}$$

By varying the pressure of the brake on the motor pulley, the output of the motor may be varied from a low value up to the full output for which the motor was designed.

Observations made upon the speed of the motor and the armature current at different loads give important information respecting the motor itself.

---

* It is here assumed that the pull is measured directly at the surface of the pulley, or in a line tangential with it, as when a band brake of negligible thickness is used. If the pull is measured at a greater distance from the shaft, owing to the thickness of the brake band, or method of applying the load, the actual pull at the pulley rim will be greater than the pull measured.

Let p^1 be the pull measured,
and $\frac{d^1}{2}$ the perpendicular distance of the centre of shaft from the line in which the pull is measured.

Then actual pull at rim of pulley $= \frac{p^1 \times d^1}{d}$, and this value must be inserted instead of p in the formulæ given above.

The curve comparing the horse-power exerted, with the current taken by a motor, is sometimes called the *Load Characteristic.*

Brakes may be arranged in the form of blocks pressed on to the pulley, and maintained in position by levers, in such a way that the tangential pull of the rotating pulley is measured by weights, or a spring balance attached to the brake lever.

Usually the most convenient form is a flexible rope or band brake wrapped round the pulley. Weights or a small spring balance attached to the free end of the band, or ropes, enable the pressure on the pulley to be varied. The other end of the brake band is fixed to some convenient point, the tension at this end being registered by a spring balance at the point of attachment. Usually it is necessary to provide small saddle-shaped wooden cleats on the brake-band, to keep the band in the centre of the pulley. Where more than 2 or 3 horse-power are to be absorbed, it usually becomes necessary to cool the pulley with water, unless the test is of very short duration, or the pulley of considerable diameter. †

In a rope brake it is the tension on the slack end of the rope which regulates the friction and tension on the whole of the rope. A comparatively small tension is sufficient where the rope is wound completely round the pulley.

A difficulty sometimes arises owing to the vibration of the pointer of the spring balance, especially if the balance is a finely graduated one. To overcome this vibration the writer has adopted a simple device, whereby steady readings may be obtained on a sensitive circular balance. This consists in attaching to the spindle immediately behind the pointer a turned brass disc having sufficient inertia to damp the small oscillations which are usually set up in the spring. The disc and the needle move together and steady readings result.

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† An approximate rule given by C. v. Bach as to the minimum size of pulleys to avoid overheating by a friction brake is as follows:—

if b = breadth of pulley in inches
d = diameter " "
HP = horse-power to be absorbed
then $bd \geqq HP \times 23{\cdot}5$ for air-cooled pulleys
or $bd \geqq HP \times 4{\cdot}7$ for water-cooled pulleys

With specially high speeds, and consequently light surface pressure, these values for bd may be slightly exceeded.

In all the usual forms of brake, the circumferential pull due to friction on the surface of the pulley is read as the difference between the readings of two balances or weighted levers, since one balance or weight is attached to the slack end of the rope and pulls in the same direction as the rotation occurs, and the other pulls in the reverse direction.

A very convenient form of brake, which is beginning to come into more general use, is a magnetic brake. This usually takes the form of a flywheel driven by the motor, the rim of the flywheel revolving between the poles of an electromagnet. By calibration at different speeds it is determined what power corresponds to definite currents used to excite the electromagnets. By reference to the curves prepared at the time of the calibration the power corresponding to any particular exciting current and speed of rotation may be read off directly.

Magnetic brakes are also arranged in such a way that the turning moment is read as the pull on the end of a lever, exactly as in a mechanical brake.

A brake of this kind is made by the Newton Electrical Works, Ltd., Taunton.

Experiment XV.—BRAKE TEST OF A SHUNT MOTOR, OR DETERMINATION OF THE LOAD CHARACTERISTIC OF A SHUNT MOTOR.

(For Diagram of Connections, see next page.)

Connections.—Connect the motor to the supply mains through a starting switch and regulating resistance, if necessary, in order to maintain the voltage constant. Put an ammeter in the main circuit. Connect a voltmeter to the motor terminals.

Instructions.—By means of the resistance R, keep the voltage at the motor terminals constant throughout the experiment.

Put the brake on the motor pulley. Begin with no load on the brake, and then put on the load gradually.

For each value of the load, read current supplied to the motor, speed and load on brake.

Repeat the readings for decreasing values of the load.

Keep the brushes in the non-sparking position throughout the experiment.

DIAGRAM OF CONNECTIONS.

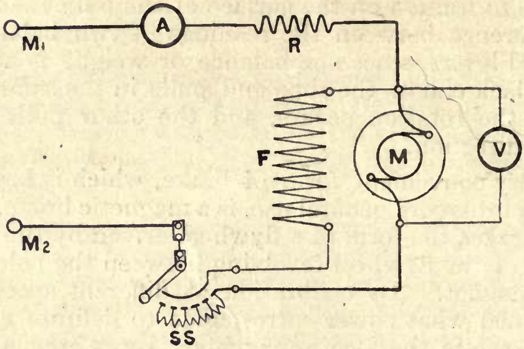

FIG. 43.

M_1 M_2	Supply mains.
M	Motor armature.
F	Motor field windings.
R	Adjustable resistance for regulating voltage at motor terminals.
A	Ammeter for measuring current supplied to motor.
V	Voltmeter for measuring voltage at motor terminals.
SS	Starting switch.

The horse-power of the motor is given by the formula

$$\text{H.P.} = \frac{2\pi r n (W - w)}{33{,}000}$$

Where W = pull* in pounds, acting at radius of pulley in contrary direction to the rotation.
w = pull in pounds acting at radius of pulley in same direction as rotation.
$W-w$ = effective pull on brake in pounds.
r = radius of pulley in feet.
n = revolutions per minute of pulley.

The readings should be entered as in the table on the following page.

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* If these forces are applied at some other effective radius from the centre of the pulley than the radius of the pulley itself, they must be increased so as to have a common moment about the shaft. See also footnote on page 125.

BRAKE TEST OF SHUNT MOTOR.

Observer........................ Date........................
Motor No. .... Type ....
Normal Output ......H.P. at ....volts, and......revs. per min.
Particulars of brake, type..............rad. of pulley ....
Voltage during test ....

Current Supplied.		Revs. per Min.	W.	*w.*	W − *w.*	Watts Supplied.	B.H.P. Supplied.	H.P. Output.	Efficiency.
Ammeter No...... Constant..........									
Reading.	True Value.		Lbs.	Lbs.	Lbs.				

From the readings entered in the Table, the following curves should be plotted, B.H.P. being in each case measured horizontally:

1. A curve showing dependence of B.H.P. exerted upon current supplied.
2. A curve showing the relation between B.H.P. and speed.
3. A curve showing the relation between efficiency $\left(= \frac{\text{output}}{\text{input}}\right)$ and B.H.P.

These curves are illustrated by the results of a trial of a $3\frac{1}{2}$ h.p. motor built by Siemens & Halske, shown in Fig. 44 (page 130).

On the same figure is added the curve of torque, calculated from the B.H.P. and speed by the formula

$$\text{H.P.} = \frac{2\,\pi\, n\, T}{33{,}000} \text{ or } T = \frac{5252 \text{ H.P.}}{n}$$

where n = revolutions per minute.
T = torque in lb.-feet.

The curve of torque should be compared with the curve of current. They are both nearly straight lines, and increase nearly in a constant ratio. The current increases, however, more rapidly as the efficiency of the motor decreases at heavy loads.

A curve comparing torque and current should also be plotted.

As already explained, the current increases in proportion to the torque to be overcome so long as the motor field remains constant.

At heavy loads, however, the internal losses of the motor will produce a weakening of the field (due chiefly to field distortion and to eddy currents), and will in other ways produce a virtual increase in the turning resistance of the armature. Consequently the current increases more rapidly than the external torque on the shaft at heavy loads.

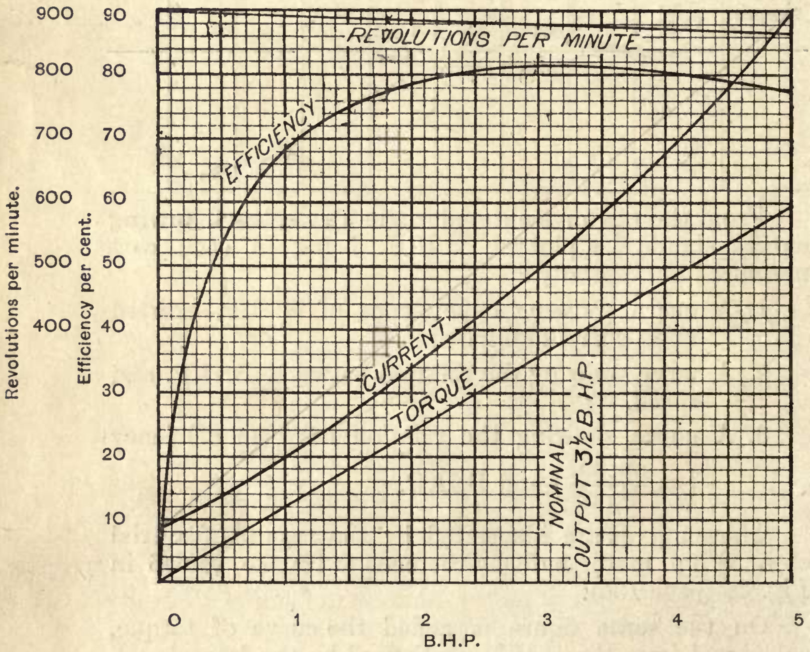

FIG. 44.—BRAKE TEST OF SHUNT MOTOR.

The curve of current does not pass through zero, as it requires a certain amount of current to excite the field magnets, to start the motor and overcome the frictional and other losses before the motor can begin to perform useful work. Even with a constant field, the curve of current would not be a straight line, because the torque (and consequently the armature current to which this is proportional) increases more rapidly than the output owing to the slowing of the motor and the increase of internal losses.

The constant exciting current and the starting current prevent the initial part of the curve passing through zero.

The curve of torque is practically a straight line, although not accurately so on account of the slight drop in the speed curve.

The efficiency is fairly constant for loads near the normal working load. A motor should have its maximum efficiency at the *usual* working load, not at its *maximum* working load.

The speed decreases slightly and regularly as the load increases within the usual limits of the output.

Since the field strength of a shunt motor is practically constant, the back E.M.F. generated in the armature is proportional to the speed. The speed of the motor can, therefore, never exceed the *critical speed*, at which the back E.M.F. becomes equal to the voltage of the source of supply. Otherwise the voltage of the motor would be higher than that of the supply.

With a *series motor* an increase of speed has the effect of diminishing the armature current, which in that case is also the exciting current. Consequently with a series motor an increase in speed weakens the field, and the speed tends still further to increase. Thus a series motor will attain an excessive speed at small loads, and be a source of danger if ever allowed to run light.

Series Motor.—A similar experiment to the last may be made on a series-wound motor. In this case it is better to begin with the full load on the brake, and gradually to decrease the load, because the motor will run at an excessive speed at light loads.

Experiment XVI.—BRAKE TEST OF A SERIES MOTOR, OR DETERMINATION OF THE LOAD CHARACTERISTIC OF A SERIES MOTOR.

Connections.—As in Experiment XV., on page 127.

Instructions.—As in Experiment XV., on page 127, except that it is best to begin with the maximum load on the brake and gradually to decrease the load until the greatest safe speed of the motor is reached.

A reverse set of readings should then be taken with increasing loads.

DIAGRAM OF CONNECTIONS.

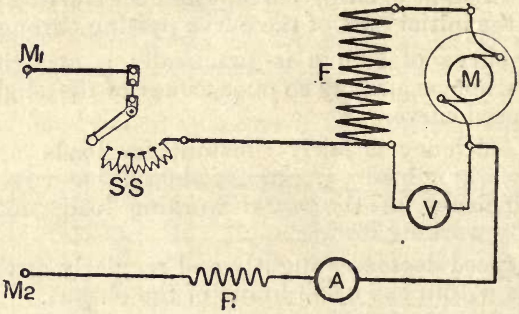

FIG. 45.

M_1 M_2	Supply mains.
M	Motor armature.
F	Motor field windings.
R	Adjustable resistance for regulating voltage at motor terminals.
A	Ammeter for measuring current supplied to motor.
V	Voltmeter for measuring voltage at motor terminals.
S S	Starting switch.

Enter results in the form given for Experiment XV., page 129.

The curves on Fig. 46 give the results of a test carried out on a 2½ horse-power 2-pole motor, built by Siemens and Halske.

The curves should be compared with those on Fig. 44 (page 130), which apply to the test of a shunt motor.

The great difference in speed variation will be seen. A shunt motor will not exceed a definite speed even when unloaded. A series motor, if insufficiently loaded, will run at an excessive speed, and will injure itself if allowed to run entirely without load. In this case also, a curve comparing torque and current with each other should be plotted.

It is to be noticed that the torque increases more rapidly compared with the current in the case of a series motor. This is because an increase in armature current causes also an increase in the excitation of the field magnets.

The torque in a shunt motor increases in the same proportion as the armature current. In a series motor the torque may increase more nearly as the square of the current, depending, however, on the saturation of the field magnets. For this reason, when running slowly, and taking a heavy current, a series motor exerts a much greater torque than a shunt motor. This is of great advantage for tramway and crane motors.

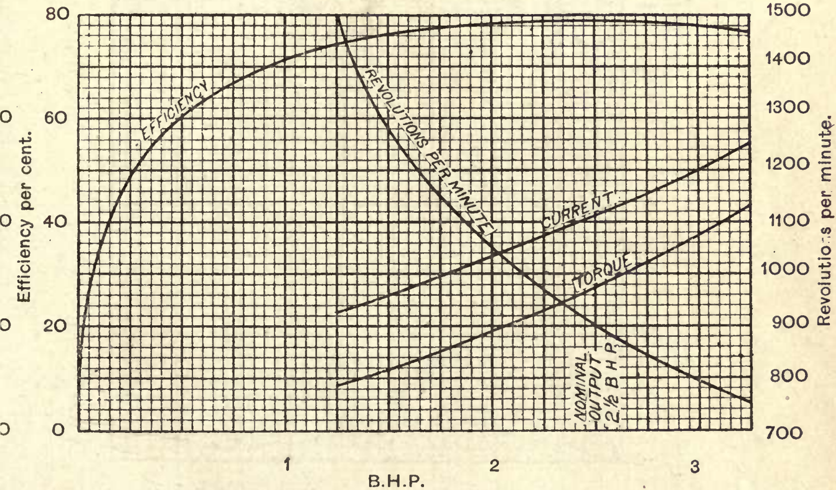

FIG. 46.—BRAKE TEST OF SERIES MOTOR.

This is also shown by the fact that the curve of torque is, in Fig. 46, no longer an approximately straight line passing through O, as in Fig. 44, but curves upwards. That is, the torque increases in a higher proportion than the output of the motor. This is also true of the current curve.

The characteristic features of a shunt motor are uniform speed, torque proportional to output, and safety against too high speeds.

The features of a series motor are heavy torque at slow speeds, variable speed tending to keep output constant, danger of running at an excessive speed with light loads.

It will be noticed that the efficiency of the series motor remains high over a considerable range of loads.

Motor Characteristic.—A curve similar to the characteristic obtained for a dynamo, comparing volts and amperes for a constant speed of revolution, may also be obtained for a motor. When taking the readings, the motor speed must be regulated by a brake, so that alteration in the voltage applied to the armature does not alter the rate of rotation of the shaft.

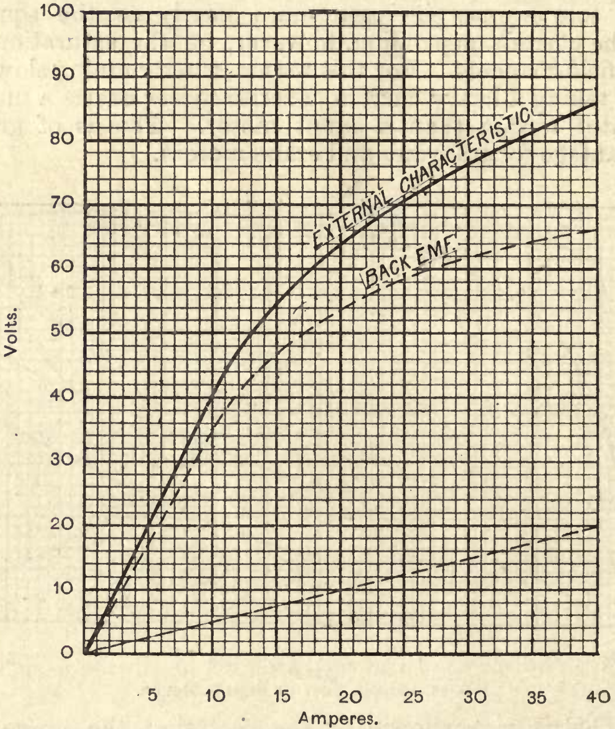

FIG. 47.—CHARACTERISTIC OF SERIES MOTOR AT CONSTANT SPEED.

The voltage applied to the armature is varied by varying the resistance in series with it. The diagram of connections is consequently the same as in Fig. 43 (page 128) for a shunt motor, and Fig. 45 (page 132) for a series motor.

For each value of the armature voltage a reading of the current is noted.

In this way the upper curve on Fig. 47 was obtained for a series motor. This corresponds to the *external* characteristic of a series dynamo (see Fig. 28, page 84). In the case of a motor the *internal* characteristic of the machine will be *below* the external curve, since the loss of voltage due to the resistance of the armature and field windings must be *subtracted* from the terminal voltage in order to give the true voltage generated in the armature.

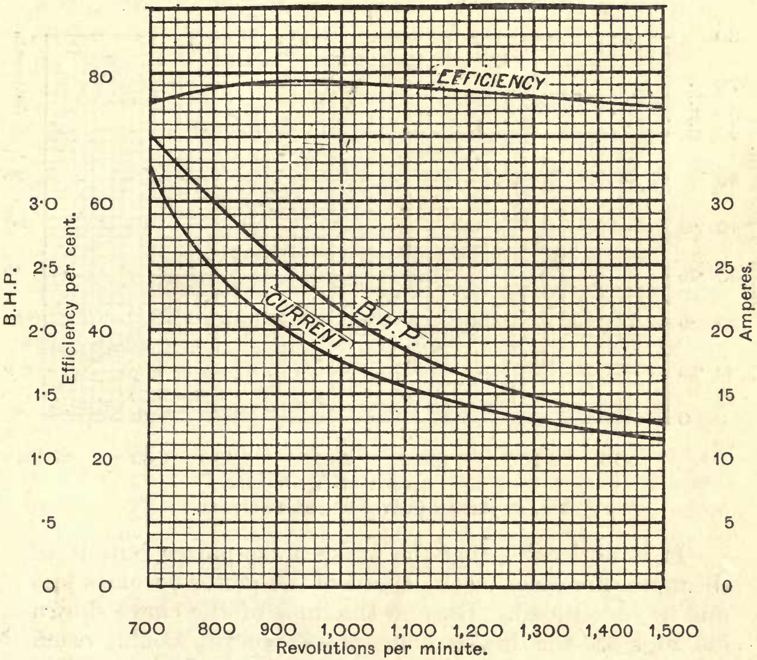

FIG. 48.—SPEED CURVES OF A SERIES MOTOR.

The voltage generated in the armature is the back electromotive force of the motor, and is got graphically from the external characteristic by drawing the sloping line shown at the bottom of Fig. 47 to represent the loss of voltage in the armature and field windings, and subtracting the height of this line from the upper curve. In this way the dotted curve marked "Back E.M.F." is obtained in Fig. 47.

Speed Curves.—The readings recorded in the curves of Fig. 46 may also with advantage be plotted in a different manner, viz., with the horizontal scale graduated in revolutions per minute. The curves so obtained are called the *speed curves* of the motor.

Fig. 48 shows the same results as Fig. 46 plotted in this way. A comparison of the two figures will make the method of drawing the curves apparent.

The speed for maximum efficiency is seen to be about 940 revs. per minute for the case shown.

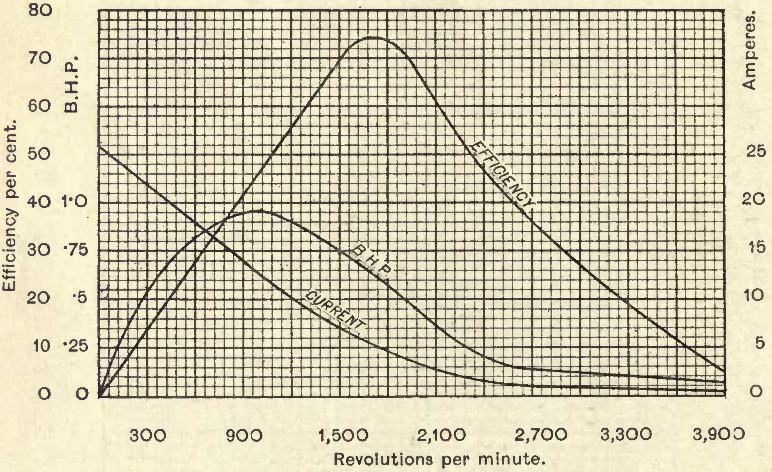

FIG. 49.—SPEED CURVES OF SERIES MOTOR.

It is noticeable that the brake horse-power output of the motor increases as the speed of the motor becomes less due to added load. Beyond the limit of the curve shown in Fig. 48 the brake horse-power curve would reach its maximum, and then rapidly fall to zero when the speed becomes zero. The current rises more rapidly than the output as the speed decreases, and attains its maximum at the point when the speed becomes nil.

The curves shown in Fig. 48 give the full range which it would be likely to meet with in practice. Greater speed on the one hand would lead to excessive vibration, and less speed, on the other hand, would involve an excessive armature current.

In order to show the general form the curves take when traced out over wider limits, Fig. 49 is given, in which similar curves are shown taken with a much smaller motor, which was capable of standing very great variations in speed without injury.*

Referring to Fig. 49, the maximum output is reached at 1,000 revs. per minute, and is seen to be nearly 1 h.p., the current taken by the motor being between 12 and 13 amperes. The efficiency reaches its maximum at about 1,700 revs. per minute, its value being 74 per cent. At this point the output is only ·65 B.H.P. At 1,000 revs., when the output is at its maximum, the efficiency is 46 per cent.

Consequently the maximum output occurs when the motor is working unfavourably as regards efficiency, while the highest efficiency is reached when the output of the motor is comparatively low.

Usually it is advisable to work at an intermediate speed, such as 1,500 revs. per minute for the motor under consideration, where the efficiency would be 70 per cent. and the output ·75 B.H.P., thus striking a mean between the point of maximum efficiency and the point of maximum output.

The most economical choice will depend upon the cost of electric power supplied to the motor and the use to which the motor is put. In cases where a high price had to be paid for current, it might be advisable to work nearly at the point of maximum efficiency, employing a comparatively large motor for the output required.

Compound-wound Motor.—From the curve given in Fig. 44, page 130, it is seen that the speed of a shunt-wound motor decreases as the load increases, owing to increased armature reactions.

By weakening the field of a motor its speed is made to increase. (Experiment XIII., page 112.)

By adding to a shunt motor a series winding, so connected that the armature current flowing in it produces a demagnetising effect on the magnets, the field will be automatically weakened by a current varying in proportion to the load. By suitably choosing the number of the series windings, the motor may be made to run at practically a constant speed, irrespective of variations of load.

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* The curves are copied from a series given in "Les Applications Mécaniques de l'Energie Electrique," by J. Laffargue.

Differential Winding.—For constant speed regulation the series winding must *oppose* the magnetising force of the shunt windings; if it is made to assist the main winding, an increased variation of speed will result.

Determination of Number of Series Windings for Constant Speed Regulation.—The number of windings required to make good a given loss in speed at full load may be calculated from the magnetisation curve of the motor, in a similar manner to the calculation of the compound windings of a dynamo required to give a constant voltage. The increase of speed will be proportional to the decrease in the magnetic field. The magnetisation curve shows the number of ampere-turns required to decrease the total flux by any given fraction of the whole.

Thus, let Fig. 12, page 39, be the magnetisation curve of the motor, and suppose that it is found that the motor, when run as a shunt machine and connected to a 110-volt circuit, makes 10 per cent. too few revolutions when fully loaded. Consequently, at full load the field must be weakened by 10 per cent. to keep the speed constant.

At 110 volts the excitation is due to $\cdot 92 \times 2{,}800 = 2{,}576$ ampere-turns, since the current is ·92 amperes and the shunt winding has 2,800 turns. In order to decrease the strength of field by 10 per cent. we must arrange to decrease the effective ampere-turns so as to correspond to a voltage 10 per cent. less than that corresponding to the fully excited shunt winding, that is to $110 - 11 = 99$ volts on the curve of Fig. 12.

This corresponds to an effective excitation of $\cdot 8 \times 2{,}800 = 2{,}240$ ampere-turns.

Hence the reverse ampere-turns $= 2{,}576 - 2{,}240 = 336$.

If the full load current is 19 amperes, the number of series windings required are $\frac{336}{19} = 18$ turns.

In this calculation the *no-load* magnetisation curve has been employed. Strictly, the full-load magnetisation curve of the motor should have been chosen, so as to make allowance for the reactions in the armature. Also at higher loads the series field drop increases, thus further decreasing the speed.

With a motor arranged to run with fixed position of brushes the error incurred would be very slight.

Instead of the magnetisation curve, the curve obtained in Experiment XIII. may be used (see Fig. 39, page 113).

The speeds on the curve corresponding to any degree of excitation will be lower at full load than shown on the curve in which the motor is taken as unloaded. The curve may, however, be taken to show what increase of speed may be expected from any alteration of excitation.

Thus a similar process to that just explained may be adopted in order to determine the requisite number of series windings for any desired *increase* in speed.

A more direct way of experimentally determining the number of windings necessary to increase the speed of a shunt-wound motor at full load is to proceed as follows:

Put an ammeter in the exciting circuit—between the field terminal of the starting switch and the field terminal of the motor—and note the exciting current. This must, of course, be done with the windings at the ordinary running temperature. Then insert an adjustable resistance in the exciting circuit in series with the ammeter.

Load the motor to its full extent, and increase the resistance in the shunt circuit until the motor runs at the required speed. Note the exciting current on the ammeter.

The ratio between the first and second readings of the ammeter—that is, the ratio between the normal exciting current and the exciting current when diminished by the shunt resistance—is the ratio which must exist between the number of ampere-turns at no load and full load, in order that the motor shall be self-regulating.

If the number of shunt windings is known, the calculation of the number of series windings is simply a matter of proportion after the full load current has been determined.

If the shunt windings are not known, the number may be estimated by one of the methods described on page 46.

If the construction of the motor allows, the series turns may be determined by trial with flexible cable wound outside the magnet bobbins to convey the armature current, the number of turns of cable being varied until the required regulation is obtained. Or, the current in a given number of turns may be varied by trial by means of an adjustable resistance put in parallel with them.

Care must be taken not to overload a compound-wound motor. If the armature current is high, current in the series winding may be sufficient to overpower the shunt winding and weaken the field to such an extent that the armature torque is not great enough to overcome the resistance of the load. The motor will then stop, and will take an excessive current unless protected by a fuse or cut-out.

This danger is especially to be guarded against in starting the motor while connected to a heavy load, as the demagnetising current is then likely to rise above its normal value.

Cumulative Winding.—Series windings connected so as to *assist* the field due to the shunt windings are sometimes employed in order that the torque of the armature may be increased under heavy loads, or at starting. The increased field when the motor is heavily loaded enables the motor to cope with heavy occasional loads without being pulled up. The speed regulation is made more variable, the variations in speed becoming more like those occurring with a series wound motor.

Transmission Dynamometers.—In the Experiments XV. and XVI., described above, the power of the motor may be looked upon as the product of two factors, viz., the torque exerted by the armature multiplied by its speed of revolution.

The torque = (force exerted at rim of pulley) × (rad.)

$$= p \times \frac{d}{2} \text{ lb.-ft.,}$$

where p = pull in lbs. measured at rim of pulley.
d = diameter of pulley in feet.
n = revolutions per minute.

Power exerted = torque × angular velocity

$$= \frac{pd}{2} \times 2\,\pi.n., \text{ ft.-lbs. per minute.}$$

In order to determine the power of a motor when working, it is, therefore, only necessary to measure by some means the *torque* exerted by the armature and the *speed.* It is not necessary to absorb the power in order to measure it, as in the experiments above described.

The speed of a motor when performing its ordinary work is easily measured by a tachometer or a hand-speed counter. The measurement of the torque exerted on the shaft usually necessitates the use of a special piece of apparatus which is known as a *transmission dynamometer*, since it measures the effort transmitted by the shaft or belt to which it is attached.

Descriptions of a number of different types of transmission and absorption dynamometers will be found in Prof. W. W. F. Pullen's book on "Experimental Engineering."

Cradle Dynamometer.—A form of absorption dynamometer in which the action of the motor fields upon the armature is directly measured is one which is sometimes convenient for use in testing small motors, especially in cases where a number of similar machines are to be tested.

In this test the motor is bolted to a small platform, which is suspended on a pair of knife edges fixed in a suitable frame, one at each end of the cradle in line with the motor shaft, and on a level with the centre of the shaft. The platform must be rigid, so as to be capable of no motion except a swinging motion about the axis of the knife edges, which is also the axis of the motor shaft.

A weight with a screw adjustment on the swinging cradle enables the motor and cradle to be so balanced that the centre of gravity of the whole coincides with the axis of suspension.

A cord is passed round the pulley of the motor, its ends being drawn tightly in opposite directions, so as to produce a braking effect on the pulley without tending to disturb the knife edges.

On supplying current to the motor, the field will tend to rotate relatively to the armature. The tendency to rotate is prevented by a spring balance, or sliding weight acting on a lever attached to the motor cradle. The armature is allowed to rotate, but the torque set up between it and the field is measured by the moment of the force applied to the lever to maintain the motor frame in its original position.

The torque is equal to the product of the weight applied and its distance from the centre of the motor shaft.

As in the case of the brake applied to the motor pulley the power is equal to

$$\frac{\pi \, pdn}{33{,}000} \text{ horse power,}$$

where p = weight acting on lever.
d = distance of weight from centre of shaft.
n = revolutions per minute.

Dynamo as Dynamometer.—An alternative method is to use a separate dynamo as a dynamometer. The dynamo is then fixed between centres or swung from knife edges, and is driven from the motor whose power is to be measured.

By means of a lever and sliding weight, or a similar device, the dynamo is kept absolutely vertical. The moment of the weight applied is then equal to the torque transmitted to its shaft by the motor.

The best method of driving is to couple the dynamo and motor together direct, but this is not always practicable. If one machine drives the other by a belt, it is difficult to arrange the knife edges so that the dynamo shall swing freely and yet take up the strain of the belt properly.

A method of driving the dynamo, which offers several advantages is to place it below the motor, suspending the dynamo pulley from the motor pulley by a short belt, which supports the whole weight of one end of the dynamo. The other end may either be mounted on a knife edge on a level with the centre of the shaft, or may be similarly suspended by a belt passing over a pulley on the other end of the shaft and running on an idle pulley above it. Side movement must be provided against by hard smooth guides. The turning moment is counteracted and measured in the same way as described above.

In carrying out the test, the motor is supplied with current and the electrical input is measured. The load on the motor is varied by varying the current produced by the dynamo and absorbed by resistances capable of suitable variation. The great advantage of such an arrangement is that the power may be absorbed in resistances placed at any distance away, and troubles owing to overheating of brake pulleys, &c., are entirely avoided.

Methods of making use of the output of the dynamo to assist in driving the motor will be described in discussing efficiency tests of dynamos.

CHAPTER XI.

EFFICIENCY TESTS OF A DYNAMO.

The efficiency of a dynamo is the ratio between the electrical power given out and the mechanical power required to drive the dynamo.

In order to obtain this ratio, both quantities must be expressed in terms of a common unit—usually the horse-power.

Since 1 H.P. is equal to 746 watts,

$$\text{Efficiency of dynamo} = \frac{\text{Output of dynamo in watts.}}{\text{Driving power in H.P.} \times 746.}$$

$$= \frac{\text{Volts} \times \text{amperes}}{\text{B.H.P.} \times 7{\cdot}46} \text{ per cent.}$$

The methods of determining the efficiency of a dynamo are of two kinds.

(1) Methods in which the driving power and the electrical output are both separately measured. These may be called the *direct* methods.

(2) Methods in which the losses occurring in the dynamo are determined by electrical measurements. These losses, when added to the output of the dynamo, give the power supplied to it. These are the *indirect* methods of measuring the efficiency.

Direct Methods of Measuring Efficiency.—Practically the only difference between the various tests of this class lies in the method of measuring the power supplied to the dynamo.

The output is always measured by a voltmeter and an ammeter. The product of the volts and amperes recorded, gives at once the output in watts.

If the dynamo is driven directly by an engine, it would suffice to know the power exerted by the engine. This is, however, not easily determined. The work performed in the engine cylinder can be estimated from indicator diagrams with a moderate degree of accuracy.

Part of the work determined in this way is spent in overcoming the losses in the engine itself, and part only is spent in driving the dynamo. The mechanical efficiency of the engine can be approximately determined by a further experiment, and in this way the power given to the dynamo may be estimated.

Such a method of determining the power supplied to the dynamo would not be nearly so accurate as the means which are available for measuring its output. The method cannot be considered satisfactory where it is the efficiency of the dynamo alone which is to be determined, and not the efficiency of the combined plant.

A method capable of giving more accurate results, and at the same time simpler in use, when once installed, is that of introducing a transmission dynamometer between the driving and driven machines.

The force exerted by one machine on the other can then be directly measured. Simultaneous readings of the speed enable the horse-power transmitted to be calculated.

Transmission dynamometers are of many types, some being coupled to the shaft, and others measuring the tension of a transmission belt. They are less frequently found in test houses than they ought to be.

Dynamo Driven by Motor of Known Efficiency.—The power supplied to a motor when doing work is very easy to measure. If the efficiency of the motor is known, the power exerted by it is capable of easy and exact measurement. If such a motor is used to drive the dynamo to be tested, the driving power and electrical output can be measured with equal accuracy.

The driving motor may be tested for efficiency by the usual brake test (Experiment XV., page 127). The test must be carried out with the motor working under as nearly as possible the same conditions as when subsequently driving the dynamo. The motor may also be tested by one of the indirect methods described later.

Usually the efficiency of the dynamo will be required while running at a given speed and giving out any currents varying between zero and some value above its normal working load. The test of the motor should in that case be carried out at a constant speed equal to the speed at which it will run when driving the dynamo. The brake load on the motor must be varied throughout the necessary range, the speed being regulated by a suitable resistance in the field circuit.

If the dynamo is to be tested at various speeds, the efficiency of the motor must similarly be first determined at the same speeds.

The method of coupling the dynamo to the motor may introduce an error of which it is difficult to determine the magnitude.

If the shafts of the machines are rigidly coupled together, increased friction in the bearings is almost certain to result. It is usually most convenient to provide the machines with pulleys, and to adopt a belt drive. The tension of the belt will cause an uncertain increase in bearing friction, and the friction and bending resistance of the belt on the pulleys will be the cause of a further loss. Under favourable circumstances, with a fairly long horizontal drive and a well used, uniform, and flexible belt, these losses may be made very small.

The best method of coupling is to connect the shafts through a flexible coupling, the driving force being transmitted by leather links or indiarubber springs, so that a slight relative motion of the shafts is always possible, and the friction on the bearings of either machine is neither increased nor decreased by the shaft of the other, since each bearing is allowed to take the full weight of its own shaft.

Where frequent tests have to be made on similar machines, the simplest method is often to couple the machines in turn to a motor whose efficiency has been carefully determined and recorded in the form of curves applicable to all the speeds and loads required.

Indirect Methods of Measuring Efficiency.—Since the power supplied to a dynamo is the sum of its useful output and the power lost in the dynamo, it is sufficient, in order to determine the efficiency, to make measurements of the output and of the lost power.

Efficiency per cent.

$$= \frac{\text{Useful power given out}}{\text{Power given out} + \text{power lost}} \times 100$$

EFFICIENCY TEST OF TWO COUPLED DYNAMOS.

For this method of testing, two similar machines are necessary. At a manufacturer's works this is usually no serious disadvantage, since it is usual to build more than one machine at once of a given type and size, or a machine of approximately the same size as the one to be tested can usually be employed temporarily.

The shafts of the two machines are coupled together. This is usually done by standing the machines in line with one another and joining the shafts by a flanged coupling, or preferably by a flexible coupling. Sometimes the machines are placed at some distance apart, and one drives the other by a belt passing over equal sized pulleys on the shafts of the two machines. In this case an additional loss of power is introduced in the friction due to the belt, also the speed of the driving machine will be slightly higher than that of the driven one, owing to the slip of the belt. The terminals of one machine are connected to those of the other.

One machine is then supplied with current, and made to act as a motor and drive the other. The current generated by the second machine is supplied to the first. In this way one machine is made to act as a generator and produce most of the current required for driving the other, which acts as a motor. The motor in turn supplies most of the power necessary to drive the generator.

Since there will be losses in both machines, a small amount of power from an external source must be supplied to keep the machines running. This power will only be the amount required to make up for the losses occurring in the two machines. The machines can in this way be made to work at full load, while only requiring a relatively small supply of power from an external source to enable the test to be carried out.

Large machines can in this way be tested at all loads without taking heavy currents from the supply mains. This is often a matter of great importance.

The losses occurring in the two machines at any load are equal to the power supplied to them in order to keep them running at this load.

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Two Coupled Machines Connected in Parallel.—Various methods of supplying the additional power have been suggested; the following method of connection to an external source of current will in general be found the most convenient. It is practically the method proposed by Kapp.

The machines are connected in parallel with each other to power mains giving voltage equal to that of the dynamos running at normal speed.

The output of the dynamo is measured by an ammeter and voltmeter, and is supplied direct to the motor.

The power supplied from the mains is similarly measured. The power given to the motor is thus the sum of the dynamo output and the power supplied from the mains. The combined efficiency of the two machines is—

$$\frac{\text{Output of dynamo.}}{\text{Input to motor.}}$$

The joint efficiency of the two machines is the product of the efficiency of each machine.

Since the machines are of the same type and size, their efficiencies should be approximately equal.*

Accordingly, it may be assumed that the efficiency of either is the square root of the combined efficiency determined by the experiment.

$$\text{Thus, efficiency of each machine} = \sqrt{\frac{\text{Output of dynamo.}}{\text{Input to motor.}}}$$

It should be noted in connection with this method of testing, that the loss of power is measured directly, and is a quantity of small dimensions compared with the output of the machines under test.

Consequently, an error of small percentage made in this measurement will be exceedingly small compared with the output of the machines, and will only affect the value of the total efficiency to a correspondingly small extent.

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* This will not be exactly true even in the case of two machines which are absolutely identical, since the efficiency of a machine when operating as a motor will be less than when working as a generator. Also the excitation of one of the machines is below the normal. The error introduced by this fact would make the efficiency of the machines appear slightly lower than its true value when working as dynamos. In most cases this error would be negligible.

In carrying out the test, the machines are connected to mains giving approximately the normal voltage of the machines.

Since[†] both machines are connected to an external source of supply (see Fig. 50) during the experiment, they would both tend to run as motors and take current equally. In order to make one act as a motor and drive the other, a variable resistance is inserted in its field circuit. This resistance weakens the field of this machine, and it consequently tends to run faster than the other. (See Experiment XIII., page 112.) By varying the field resistance, the power exerted by the motor upon the dynamo can be varied. The power given out by the dynamo will vary concurrently.

Experiment XVII.—Determination of the Efficiency of Two Coupled Dynamos or Motors Connected in Parallel.

Diagram of Connections.

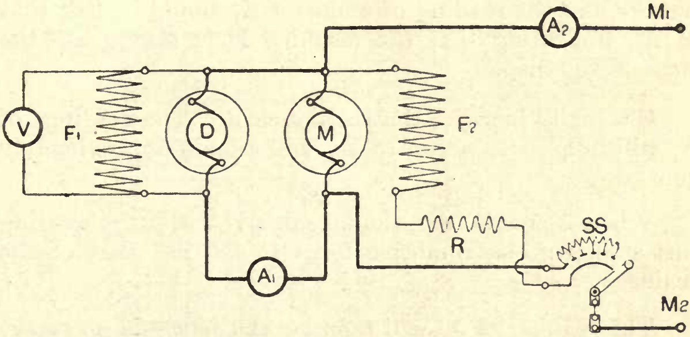

FIG. 50.—EFFICIENCY OF TWO SIMILAR MACHINES COUPLED TOGETHER.

M_1 M_2	Supply mains.
D	Armature of machine running as generator.
M	Armature of machine running as motor.
F_1 F_2	Field windings of the two machines.
R	Variable resistance for weakening motor field
A_1	Ammeter indicating output of generator.
A_2	Ammeter indicating current supplied from mains.
V	Voltmeter indicating voltage at terminals of machines.
SS	Starting switch.

[†] In the arrangement described below the power lost in the machines is supplied from the mains. In some cases it is more convenient to use a battery or small auxiliary machine for the purpose. In the original description by Hopkinson the power was supplied in the form of mechanical energy by a small steam engine.

Connections.—Couple the two machines together mechanically.

Connect one machine to the supply mains, or other source of current having a voltage equal to the normal voltage of the dynamos to be tested, through a starting switch, putting an adjustable resistance in series with the field winding, and an ammeter in the main circuit.

Connect the terminals of the second machine to those of the first one, inserting an ammeter in one of the connections.

Connect the field windings of the second machine in shunt with the armature, and connect a voltmeter to the machine terminals.

Instructions.—Begin with the shunt resistance R cut out. Start the motor by switching the starting switch over slowly. Both machines will then be driven as motors, and the reading of ammeter A_1 should be half that of A_2, indicating that the machine D is taking half the current supplied.

Gradually increase the resistance R. The readings of A_1 will fall, while those of A_2 will remain approximately constant.

When A_1 reads zero, the machine D will be generating just sufficient electromotive force to balance that of the mains.

The reading of A_2 will then be the current necessary to run both machines at no load.

On increasing R further, the current through A_1 will be reversed, since D will now begin to supply current, instead of receiving it.

Gradually increase R until A_1 registers the full load current of the machines.

For each value of the resistance read the load current on A_1, the loss current on A_2, and the voltmeter V. Note also the speed.

Enter results as in the following table :—

DETERMINATION OF THE EFFICIENCY OF TWO COUPLED DYNAMOS WITH ARMATURES CONNECTED IN PARALLEL.

Observer .... Date ....

Dynamo Nos. ....and..... Type ....

Normal output........volts..... amps., at........revs. per minute.

Revs. per Minute.	Generator Current = c	Generator Volts = v	Power given by Generator = $c \times v$	Current from Mains = c^1	Power given to Motor = $(c+c^1)\,v$	Efficiency of Pair.	Efficiency of each Dynamo.

Plot a curve showing the dependence of efficiency upon current generated, plotting the output of the generator horizontally in amperes and the efficiency per cent. vertically.

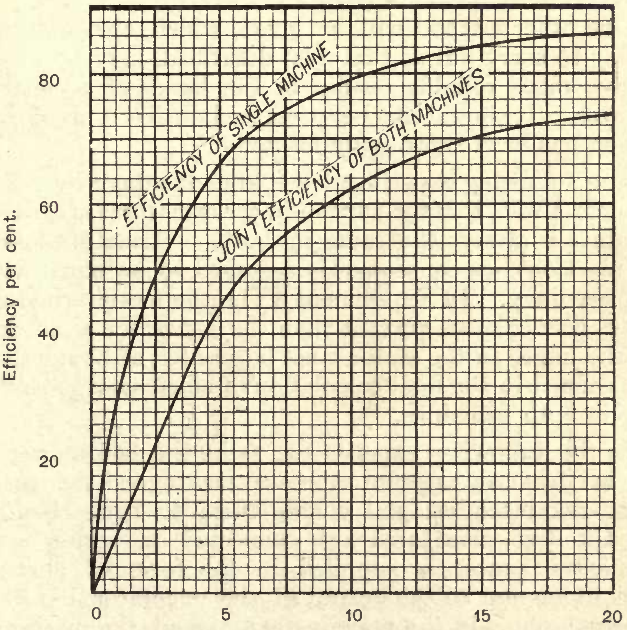

FIG. 51.—EFFICIENCY OF TWO COUPLED DYNAMOS.

Both the joint efficiency of the two machines taken together, and the square root of this, representing the efficiency of each machine, should be plotted.

This is shown on Fig. 51, the upper curve showing directly the efficiency of a single machine at various loads.

Two Coupled Dynamos Connected in Series.—In the test just described, the current generated by one machine is used for driving the other machine, which acts as a motor. Owing to the losses occurring in the two machines, the current generated in the armature of the generator is not able to supply all the current required to drive the motor. The additional current required to drive it is supplied from an external source. The losses occurring in the system are consequently measured by the amount of additional current required by the motor.

Experiments in which machines are coupled together, so that one machine supplies part of the power required to drive the other, may be carried out in a considerable number of other ways.

One other method will be given, which, although not so easy to carry out as that just described, may be made to give more reliable results in the hands of a capable observer. It should not be attempted until the preceding method has been thoroughly mastered.

The following experiment has the advantage over Experiment XVII., that the current in the armatures of the two machines is always the same in both. Armature losses and reactions are consequently assumed to be equal with more accuracy. In Experiment XVII. the motor armature always carries more current than the generator armature, and the losses in the motor must be greater, although they are assumed in the final calculation of efficiencies to be the same in both machines.

In the following experiment, as in the last, power is supplied from an external source to make good the losses in the two machines and enable them to run. In this case the two armatures are connected in series, and this extra power is supplied in the form of current equal in amount to the output of the generator, but at a lower voltage. In the previous experiment the machines were coupled in parallel instead of in series, and the extra power consisted of a supply of current at practically the same voltage as that of the machines being tested, but small in amount.

The chief difference between Experiments XVII. and XVIII. lies in the fact that in Experiment XVII. the lost power is supplied from an external source capable of giving a small current at the full voltage of the machines to be tested; whereas in Experiment XVIII. the power supplied is of low voltage, but of the same current strength as the machines under test. In Experiment XVII. the two machines are supplied from the external source in parallel. In Experiment XVIII. the machines are connected in series with each other, and with the source of supply.

The connections for the experiment are shown below (Fig. 52), the machine M acting as a motor to drive the machine D, which acts as a generator and contributes to the supply of power given to the armature of M. It will be seen that the two armatures are connected in opposition, brushes of the same polarity (marked + in the figure) being joined together.

In consequence of this method of connection the — brush of the generator D is shown to be connected to the + terminal of the source of supply. The generator is thus connected in series with the supply source in such a way as to add its voltage to that of the source. Consequently the voltage available at the terminals of the machine M is the sum of the voltages of D and of the source of supply.

It must be observed that in this experiment it is the machine with the more strongly-excited field which acts as motor. This is the reverse of what occurred in Experiment XVII., where the machine whose field was weakened took more current and acted as motor. The reason for this difference arises from the fact that in the present case the current in both armatures is necessarily the same; also from the way in which the machines are connected they will try to rotate in opposite directions. It is, therefore, the machine which can exert the stronger turning effort which will determine the direction of rotation, and drive the other machine. The stronger torque is obviously exerted by the machine having the more strongly-excited magnets, since the armature current is the same in both.

It is this machine which becomes the motor, and drives the other as a generator.

Experiment XVIII.—Determination of the Efficiency of Two Coupled Dynamos with Armatures Connected in Series.

Diagram of Connections.

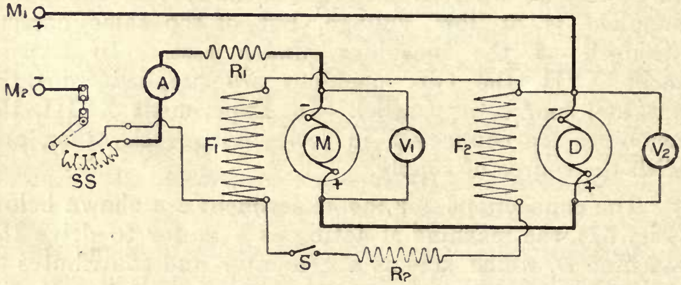

Fig. 52.—Diagram of Connections of Two Coupled Dynamos Connected in Series.

M_1 M_2*	Supply mains, or terminals of auxiliary machine.
D	Armature of machine acting as generator.
M	Armature of machine acting as motor.
F_1 F_2	Field windings of machines.
R_1	Adjustable resistance for regulating voltage of supply.
R_2	Adjustable resistance for regulating field excitation of machine D.
A	Ammeter for measuring load current.
V_1 V_2	Voltmeters for measuring voltage of the two machines.
S	Switch for breaking generator exciting circuit.
S S	Starting switch.

Connections.—Connect the armatures of the two machines in series with each other and with the auxiliary machine, or other source of supply, which is to provide the additional power. Insert in the same circuit an ammeter and variable resistance.

---

* The diagram (Fig. 52) shows the connections which are most convenient for carrying out the test on small machines where the power is derived directly from the mains, and economy in the power used is not important. Some modifications to be adopted in carrying out the tests on a larger and more economical scale are given later.

Connect the field windings of both machines to a source of current having sufficient voltage to supply the normal exciting current to the windings. The windings of the machines must be connected to the source in parallel so that the current in each can be regulated independently of the other.

In the exciting circuit of the machine which is to act as generator insert an adjustable resistance.

Connect a voltmeter to the terminals of each machine.

In connecting up the machines, care must be taken to join together terminals of the same polarity. If the machines are wrongly joined, they will both tend to rotate in the same direction, and will both act as motors, dividing up the voltage of the source of supply between them approximately in proportion to their exciting currents.

To test the correctness of the connections (if this is not easily ascertainable by an inspection of the machines), a voltmeter of the permanent magnet type may be employed. This should show deflections in the same direction when one of its terminals is connected to the conductor joining the machines, and its other terminal is connected alternately to the opposite terminals of the two machines.

In carrying out the test on large machines it will not generally be possible to use a single starting switch for armature and field current, as shown in Fig. 52. In such cases the voltage required for the excitation will be considerably higher than that necessary for the armature circuit. It would be very wasteful to absorb the difference in voltage in a resistance, as shown in the figure at R_1. In carrying out the test on a commercial scale it is therefore usual to excite the fields from a convenient source—say the power circuit of the test house—and to employ a variable-voltage motor-generator or booster† to supply the current for the armature circuit. The voltage of the source supplying the armature circuit is then regulated by means of a resistance in the auxiliary generator or booster field, instead of by the resistance R_1 in the circuit of the machines tested.

Instructions.—Commence supplying current to the two machines with the switch S in the field of the generating machine open. Machine M will be driven by the current, its speed depending on the voltage applied. The armature of machine D will merely act as part of the circuit, carrying the current but not offering any resistance to the rotation.‡

---

† The methods of operation of a motor-generator and booster are described later. (Experiments XXVII. to XXIX.)

Adjust R_2 to its maximum value (which should be several times the resistance of the field winding), and then close S. Machine D will at once begin to generate, adding its voltage to that already supplying M. Consequently M will immediately increase its speed as a result of the increased voltage at its terminals.

The voltage of the supply should now be regulated until the machines run at their normal speed. When this is arranged, the ammeter and both voltmeters are read.

By giving to R a succession of different values, and regulating the supply voltage in each case until normal speed is attained, a series of readings will be obtained, each reading corresponding to a different value of the output current of the generator.

In each case the output of the generator is obtained in watts by multiplying the armature voltage by the current. Similarly, the power supplied to the motor is the product of its armature voltage and the current. Consequently, the combined efficiency of the two machines is given by the fraction

$$\frac{(\text{Main current}) \times (\text{voltage of generator})}{(\text{Main current}) \times (\text{voltage of motor})} = \frac{\text{voltage of D}}{\text{voltage of M}}$$

As explained in the case of Experiment XVII., the efficiency of each machine is the square-root of the combined efficiency if the efficiencies of the two machines are equal. Consequently we may write

$$\text{Efficiency of each machine} = \sqrt{\frac{V_2}{V_1}}$$

where V_1 V_2 are the voltages of the motor and generator respectively.

In this calculation the losses due to the current spent in excitation is neglected. The amount of power spent in the excitation of each machine under normal conditions of working is the product of the exciting current (in amperes) multiplied by the voltage at which it is supplied to the field winding.

---

‡ Under these conditions a slight *negative* deflection may be observed on the voltmeter V_2, due to the fall of voltage experienced by the current in flowing through the resistance of the armature of D.

Hence, in order to allow for this loss, we must consider the total power supplied to drive two machines to be equal to CV_1+2cV, and consequently,

$$\text{Efficiency of 2 machines} = \frac{C\,V_2}{C\,V_1 + 2c\,V}$$

Where C=armature current.
c=normal exciting current.
V=normal voltage of excitation.

∴ Efficiency per cent. of each machine

$$= \sqrt{\frac{C\,V_2}{C\,V_1 + 2c\,V}} \times 100$$

Tabulate results as in the following table :

DETERMINATION OF EFFICIENCY OF TWO COUPLED DYNAMOS WITH ARMATURES CONNECTED IN SERIES.

Observer...................... Date..........................
Dynamos Nos. ......and...... Type..........................
Normal output........volts.........amps., at......revs. per minute.
Normal exciting current..........amps.

Output Current $= C$	Motor Voltage $= V_1$	Generator Voltage $= V_2$	Watts supplied to Machines $= C\,V_1+2\,c\,V$	Watts output of Generator $= C\,V_2$	Combined Efficiency $= \frac{C\,V_2}{C\,V_1+2\,c\,V}$	Efficiency of each machine $= \sqrt{\frac{C\,V_2}{C\,V_1+2\,c\,V}}$

Two curves should be plotted from the results recorded, viz., one curve showing the variation of the combined efficiency of the machines with the current output of the generator; and one curve showing the variation in the efficiency of a single machine. In each case the armature current should be plotted horizontally and the efficiency measured vertically. The results will be similar to those shown on Fig. 51.

The special difficulties to be met with in carrying out this experiment are due to the difficulty in regulating the speed of the machines, so that they may give the desired current at the normal speed. A very slight alteration to the generator field will in some cases cause a very great change in speed and current, which it is extremely difficult to bring back to their normal value.

Except for the comparatively small variations in the armature reactions of the motor, the speed would be proportional to the voltage V_1 of the motor armature. Consequently the readings of V should be kept nearly constant, increasing slightly at the higher loads. This forms a guide in adjusting the resistance R_2 in the generator field.

SWINBURNE'S ELECTRICAL METHOD OF TESTING EFFICIENCY.

In this method the losses occurring in a dynamo are determined, and the efficiency is calculated from the formula

$$\text{Efficiency} = \frac{\text{output}}{\text{input}} = \frac{\text{output}}{\text{output} + \text{losses}}.$$

The experiment consists of two parts.

First, the losses due to power spent in excitation and in the armature resistance are calculated. In each case this power is the resistance multiplied by the square of the current flowing in it :

$$\text{Watts} = C^2R.$$

The second part of the experiment is a determination of the other losses, or "stray power." These are due to

Friction of the journals, brushes, and air.

Hysteresis losses in the armature core.

Induced local currents, or eddy currents formed chiefly in the armature core plates.

These losses can be measured by running the dynamo as a motor without load, the field being separately excited to the normal extent, and the armature being supplied with current sufficient to make it run at full speed. The power taken by the armature under these conditions is that necessary to overcome the losses due to friction, hysteresis, and eddy currents.

Experiment XIX.—DETERMINATION OF EFFICIENCY OF A SHUNT DYNAMO BY SWINBURNE'S METHOD.

The losses to be determined in a shunt dynamo are as follows :—

(1) Power expended in excitation of field.
(2) Power lost in heating armature, brushes, &c.
(3) Power lost in friction, hysteresis, and eddy currents.

Let it be desired to determine the efficiency of the dynamo at full load, $\frac{3}{4}$ load, $\frac{1}{2}$ load, and $\frac{1}{4}$ load respectively.

Instructions.—Run the dynamo at full load and normal speed until its windings have become warmed up to a stationary temperature.

Read the voltage of the dynamo, and the current in the shunt windings.

Stop the machine and measure the resistance between its terminals while still hot, first disconnecting the field and main circuit, so as to obtain the resistance of armature, brushes, and connections, as in Experiments I.—III., pages 6 and seq.

Repeat these readings at $\frac{3}{4}$, $\frac{1}{2}$, and $\frac{1}{4}$ load respectively if extreme accuracy is necessary. Usually the armature and field resistances may be assumed to be constant at all working loads.

Determination of Losses (1).—The power spent in excitation is the product of the current in the field windings, and the voltage at their terminals.

Enter results thus :—

TABLE I.

	Main Current.	Shunt Current $= c$	Voltage $= E$	Watts lost in Shunt $= cE$.
Full load				
$\frac{3}{4}$ load				
$\frac{1}{2}$ load				
$\frac{1}{4}$ load				

Determination of Losses (2).—The total current in the armature will be the sum of the currents measured in the main circuit and shunt circuit, *i.e.*, the sum of the currents entered in columns 1 and 2 of Table I. above.

Call this current C, and let R be the measured resistance between the armature terminals. Then $C^2 R$ will be the number of watts spent in heating the armature conductors, &c.

Tabulate values as in table on the following page.

TABLE II.

	Armature Current = C	Armature Resistance = R	Watts lost in Armature Conductors = $C^2 R$
Full load........			
$\frac{3}{4}$ load			
$\frac{1}{2}$ load			
$\frac{1}{4}$ load			

Determination of Losses (3).—

Let W = output of dynamo in watts.
w = sum of watts lost in shunt and armature conductors.
= sum of quantities in last columns of Tables I. and II.
C = total armature current (column 1, Table II.).
V = total voltage generated in armature.

$$= \frac{W + w}{C}$$

NOTE.—All the above quantities will have different values at different loads.

A further experiment is now necessary.

DIAGRAM OF CONNECTIONS.

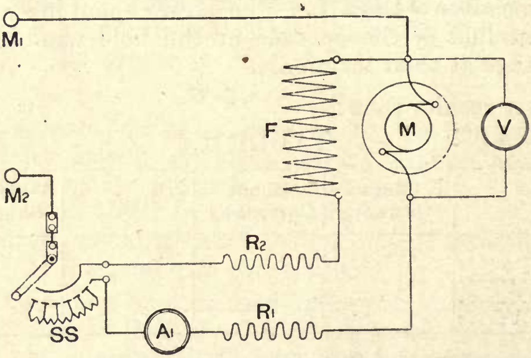

FIG. 53.—SWINBURNE'S TEST.

M_1 M_2	Supply mains.
M	Machine armature.
F	Machine field windings.
R_1	Adjustable resistance for varying voltage at armature terminals.
R_2	Adjustable resistance for regulating exciting current.
A_1	Ammeter for measuring armature current.
V	Voltmeter for measuring volts across armature.
SS	Starting switch.

Connections.—Connect the dynamo to the mains to run as a motor. Insert variable resistances in both shunt and armature circuits.

Connect a voltmeter to the dynamo terminals, and an ammeter in series with the armature.

Instructions.—Commencing with the shunt resistance cut out, start the machine.

Adjust the resistance R_1 in series with the armature until the voltage at the armature terminals is equal to V (see above).

Measure the speed. Probably it will be below the normal speed of the dynamo on account of the small magnetic reaction of the armature. Increase the shunt resistance R_2 until the machine runs at normal speed.

When running at normal speed, and receiving a voltage equal to V at the terminals, read the armature current on ammeter A.

Call this current C^1.

Repeat this reading for each value of V for which the efficiency is to be measured.

Tabulate thus :—

TABLE III.

	Amperes = C^1	Volts = V	Watts lost in Friction, &c. = $C^1 V$
Full load........			
¾ load			
½ load			
¼ load			

Summary of Results.—The efficiency of the dynamo is now obtained by adding the losses together and comparing them with the useful output at each value of the load.

$$\text{Efficiency per cent.} = \frac{\text{Watts output}}{\text{Output} + \text{losses}} \times 100.$$

Summarise results thus :—

TABLE IV.

	Watts spent in Excitation.	Watts lost in Armature Conductors.	Watts lost in Friction, Hysteresis, &c.	Total Watts Lost.	Watts Output.	Power supplied = output + losses.	Efficiency per cent.
Full load..							
¾ load							
½ load							
¼ load							

This method of testing is equally applicable to shunt, series or compound dynamos. The only difference lies in the method of calculation of the losses in the field and armature conductors, since the amount of current flowing in them will be different in each case.

Thus, in a series dynamo the armature current is equal to the current in the external circuit. In a shunt dynamo it is equal to the external current + the shunt current. Also the losses in the field windings will vary for each case.

The following calculation, carried out in detail for the most general case of a compound dynamo, will make the difference clear.

The test was carried out on a small Crompton dynamo.

Dynamo No. 9,012. *Type*, 2-pole drum wound.

Normal output, 20 amperes 150 volts, at 1,450 revs. per minute.

Field windings connected in short shunt.

Resistance of armature (hot) ... ... ·18 ohm
Resistance of series winding (hot) ... ·07 ,,
Resistance of shunt winding (hot) ... 95·0 ,,

Observed voltage at terminals—
(1) Full load or 20 amperes ... ... 150 volts.
(2) ¾ ,, or 15 ,, ... 150 ,,
(3) ½ ,, or 10 ,, ... 152 ,,
(4) ¼ ,, or 5 ,, ... 151 ,,

Calculated drop in armature conductors—
(1) at 20 amperes = 21·59 × ·18 = 3·9 volts.
(2) at 15 ,, = 16·58 × ·18 = 2·9 ,,
(3) at 10 ,, = 11·6 × ·18 = 2·1 ,,
(4) at 5 ,, = 6·59 × ·18 = 1·2 ,,

Current taken by machine when run light as a motor at full speed with voltage applied to armature equal to the total voltage generated when driven as a dynamo was as follows:—

Voltage Applied.	Current.	Watts Absorbed.
153·9	·754	153·9 × ·754 = 116 watts.
152·9	·75	152·9 × ·75 = 114·5 ,,
154·1	·754	154·1 × ·754 = 116 ,,
152·2	·74	152·2 × ·74 = 112·3 ,,

Summary of Losses.—

(1) *At full load*—

Drop in series coils $= \cdot 07 \times 20 = 1 \cdot 4$ volts.

Shunt current $= \dfrac{151 \cdot 4}{95} = 1 \cdot 59$ amps.

Total armature current $= 21 \cdot 59$ amps.

Loss in armature conductors $= 21 \cdot 59^2 \times \cdot 18 = 84 \cdot 8$ watts.

Loss in shunt coils $= 1 \cdot 59 \times 151 \cdot 4 = 242 \cdot$,,

Loss in series coils $= 20^2 \times \cdot 07 = 28 \cdot$,,

Losses in driving machine $= 153 \cdot 9 \times \cdot 754 = 116 \cdot$,,

Total losses ... ... 470·8 ,,

Output ... ... 3,000·0 ,,

Input ... ... 3,470·8 ,,

$$\therefore \text{Efficiency} = \frac{3{,}000 \times 100}{3{,}470 \cdot 8} = 86 \cdot 4 \text{ per cent.}$$

(2) *At $\frac{3}{4}$ load*—

Drop in series coils $= \cdot 07 \times 15 = 1 \cdot 05$ volts.

Shunt current $= \dfrac{151 \cdot 05}{95} = 1 \cdot 58$ amps.

Total armature current $= 16 \cdot 58$ amps.

Loss in armature conductors $= 16 \cdot 58^2 \times \cdot 18 = 49 \cdot 5$ watts.

Loss in shunt coils $= 1 \cdot 58 \times 151 \cdot 05 = 238 \cdot 5$,,

Loss in series coils $= 15^2 \times \cdot 07 = 15 \cdot 7$,,

Loss in driving machine $= 152 \cdot 9 \times \cdot 75 = 114 \cdot 5$,,

Total losses ... ... 418·2 ,,

Output ... ... 2,250·0 ,,

Input ... ... 2,668·2 ,,

$$\therefore \text{Efficiency} = \frac{2{,}250 \times 100}{2{,}668 \cdot 2} = 84 \cdot 3 \text{ per cent.}$$

(3) *At $\frac{1}{2}$ load*—

Drop in series coils $= \cdot 07 \times 10 = \cdot 7$ volts.

Shunt current $= \dfrac{152 \cdot 7}{95} = 1 \cdot 6$ amps.

Total armature current $= 11 \cdot 6$ amps.

Loss in armature conductors $= 11{\cdot}6^2 \times {\cdot}18 = 24{\cdot}3$ watts.
Loss in shunt coils $= 1{\cdot}6 \times 152{\cdot}7 = 244{\cdot}4$,,
Loss in series coils $= 10^2 \times {\cdot}07 = 7{\cdot}0$,,
Loss in driving machine $= 154{\cdot}1 \times {\cdot}754 = 116{\cdot}$,,

Total losses ... ... 391·7 ,,
Output ... ... 1,520· ,,

Input ... ... 1,911·7 ,,

$$\therefore \text{Efficiency} = \frac{1520 \times 100}{1911{\cdot}7} = 79{\cdot}5 \text{ per cent.}$$

(4) *At ¼ load*—

Drop in series coils $\cdot 07 \times 5 = {\cdot}35$ volts.

Shunt current $\dfrac{151{\cdot}35}{95} = 1{\cdot}59$ volts.

Total armature current 6·59 amps.

Loss in armature conductors $= 6{\cdot}59^2 \times {\cdot}18 = 7{\cdot}8$ watts.
Loss in shunt coils $= 1{\cdot}59 \times 151{\cdot}35 = 241{\cdot}0$,,
Loss in series coils $= 5^2 \times {\cdot}07 = 1{\cdot}75$,,
Loss in driving machine $= 152{\cdot}2 \times {\cdot}74 = 112{\cdot}4$,,

Total losses... ... ... 362·95 ,,
Output ... ... 755 ,,

Input ... ... 1,117·95 ,,

$$\therefore \text{Efficiency} = \frac{755 \times 100}{1{,}117{\cdot}95} = 67{\cdot}5 \text{ per cent.}$$

These results of this test are shown graphically on the curve given in Fig. 54. The curve is continued so as to pass through zero.

This method of testing, in common with several other indirect methods, has the disadvantage that the losses are determined in the machine when running with small armature current.

The assumption that the losses due to hysteresis and eddy currents are the same at heavy loads as when the armature carries small currents is not accurate, although sufficiently so for approximate or comparative measurements.

EXAMPLE OF DETERMINATION OF EFFICIENCY OF A COMPOUND-WOUND DYNAMO BY SWINBURNE'S METHOD.

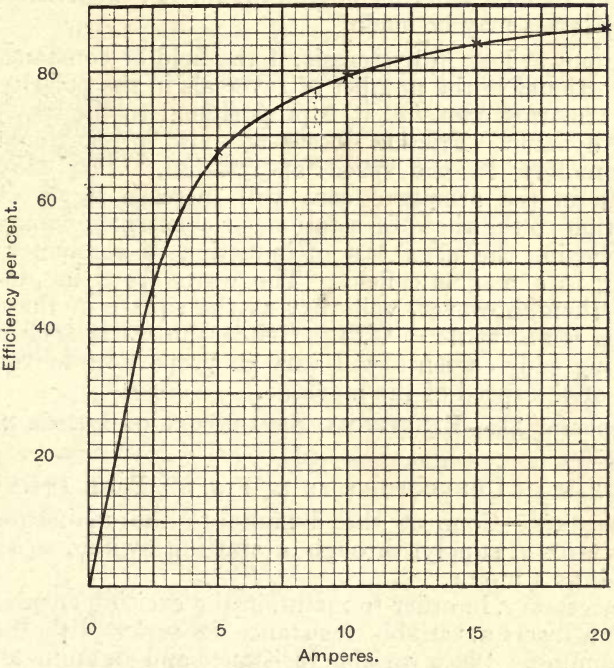

FIG. 54.—EFFICIENCY OF DYNAMO BY SWINBURNE'S METHOD.

FURTHER SEPARATION OF LOSSES.

In order to gain as much insight as possible into the causes of the losses occurring in a dynamo, it is useful to be able to determine the amount of the losses due to their several causes. In this way it is possible to detect excessive losses due to eddy currents arising from insufficient lamination of the armature core, or too great hysteresis losses caused by inferior iron.

General Principles.—In the description of Swinburne's method of testing efficiency, it was explained how the watts spent in heating the armature conductors and exciting the field magnets are determined. No further separation of the losses occurring in the armature, due to hysteresis in the iron core, eddy currents in the core plates, and friction in the various parts of the machine was attempted. The sum of these losses was determined by measuring the watts required to drive the machine as an unloaded motor, with the field separately excited.

By an extension of this method the further subdivision of these losses may be made.

The power lost in hysteresis, if the field be constant, is proportional to the number of reversals in the polarity of the armature core, *i.e.*, it is proportional to the speed of the dynamo. Friction losses are also proportional approximately to the speed of rotation. The eddy currents in the armature core will increase in direct proportion to the speed of rotation for constant inducing field, obeying the usual law of induction in conductors rotating in a magnetic field. The watts spent in producing them, however, will vary as the square of these currents (since watts $= C^2R$). Hence the watts lost in producing eddy currents will vary in proportion to the square of the speed of the machine.

Experiment XX.—ELECTRICAL SEPARATION OF LOSSES IN A DYNAMO.

DIAGRAM OF CONNECTIONS AS IN FIG. 53, PAGE 160.

Connections.—Connect the dynamo to the mains (or other source of supply) through a starting switch, so as to run it as a motor.

If necessary, in order to maintain the exciting current constant, insert a variable resistance in series with the field winding. Put a variable resistance and an ammeter in the armature circuit.

Connect a voltmeter to the machine terminals.

Instructions.—(*a*) Excite the machine with its normal exciting current.

Supply current to the armature through the variable resistance. Measure the armature current and the volts at the terminals of the machine. Repeat the readings with several values of the resistance in the armature circuit, while maintaining the exciting current constant, so as to obtain as wide a range of armature voltage as possible. The speed of the machine will vary.

Enter readings thus :—

Armature Current.	Armature Voltage.	Exciting Current (constant).

(*b*) Repeat the readings with one or two values of the exciting current, respectively below and above the normal, keeping the exciting current constant for each series of readings.

Enter readings as before.

For the further separation of the losses the dynamo is coupled to a small motor whose efficiency is known, and the power taken by the motor when driving the dynamo under various conditions is measured.

The power spent in driving the dynamo is equal to the number of watts supplied to the motor multiplied by the efficiency of the motor.

(*c*) Excite the magnets of the machine with the normal current, and connect the armature terminals to a voltmeter.

Drive the dynamo by means of a motor at the speed at which the dynamo gives its normal voltage. Measure the speed, and the volts and amperes taken by the motor.

Enter results thus :—

Generator volts ... ...
Generator speed ... ...
Motor volts ... ...
Motor amperes ... ...
Watts supplied to motor (= volts × amps.) ... ...
Watts spent in driving dynamo (= watts supplied to motor × efficiency).

(*d*) Interrupt the excitation of the dynamo, and again drive by the motor at the same speed as before. Note the volts and amperes taken by the motor. The watts supplied to the motor will be less than when the dynamo field was excited. The difference* represents the power absorbed by hysteresis and eddy currents, since these losses do not occur with the fields unexcited.

Enter results as on next page.

---

* There will still be the "residual magnetism" remaining in the magnets. This will be so small in amount as to be negligible in most cases. If necessary, the magnets can be demagnetised by sending an alternating current round them, and gradually decreasing the strength of this current to zero.

Generator speed ... ...
Motor volts ... ...
Motor amperes ... ...
Watts supplied to motor ... ...
Watts spent in driving dynamo ...
Watts due to hysteresis and eddy currents in generator ... ...

(The last item is got by subtracting the "watts spent in driving dynamo" from those obtained in the previous experiment (*d*).)

(*e*) Lift the brushes off the commutator of the dynamo and again drive at the same speed by the motor. Measure motor volts and amperes, and enter results as before :—

Generator speed ... ...
Motor volts ... ...
Motor amperes ... ...
Watts supplied to motor ... ...
Watts spent in driving dynamo ...
Watts due to friction of generator brushes... ... ...

(The last item is the difference between the "watts spent in driving dynamo" of the last two experiments (*d*) and (*e*).)

Plotting of Curve and Explanation.—The readings obtained as in (*a*) must be plotted on squared paper, volts horizontally and amperes vertically, for each reading. The results should give points on a straight line *A B* (see Fig. 55), cutting the vertical axis in *A*.

With a motor having constant excitation and running light, the speed is proportional to the terminal voltage applied. (See Experiment XIV.) Consequently, horizontal distances on the curve are proportional to speeds of rotation.

Consider the readings represented by any point *p* on the line *A B*. (See Fig. 55.) The power absorbed by the motor, when running under the conditions represented by this point, is the product of the amperes and volts represented by the lines *pm pn* respectively.

Thus the rectangle *pnOm*, which is equal to *pm* × *pn*, represents the power taken by the motor to enable it to overcome the losses in its armature.

Draw *Aq* horizontal, cutting *pm* in *q*.

It will be shown that the rectangle *nAqp* is proportional to the square of the distance of *p* from *On*, whereas the rectangle *AOmq* is directly proportional to the distance of *p* from *On*. Thus the area *nAqp* represents the power supplied to the motor to overcome the losses which increase proportionately to the square of the speed of the dynamo, while the area of *AOmq* represents the losses which are simply proportional to the speed.

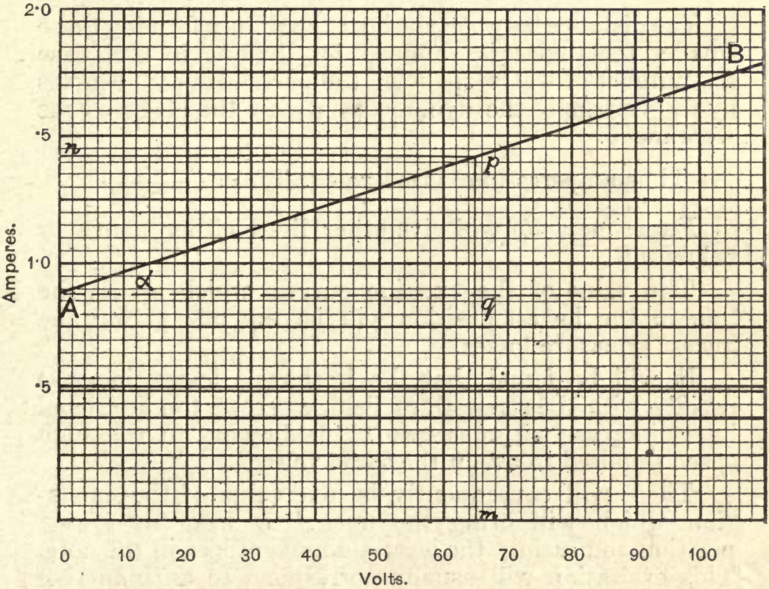

FIG. 55.—SEPARATION OF LOSSES IN A DYNAMO.

Let the angle $p\ A\ q$ be α, which is constant for the machine.

$$\text{Area of } n\ A\ q\ p = p\ q \,.\, A\ q$$
$$\text{Also } p\ q = A\ q \,.\, \tan \alpha$$
$$\therefore \text{area } n\ A\ q\ p = (Om)^2 \tan \alpha,$$

i.e., it is proportional to the square of the voltage corresponding to *p*, or proportional to the square of the speed, since the speed is proportional to the voltage.

The area of $A\ O\ m\ q = A\ O \,.\, O\ m$, and, since $A\ O$ is a constant length, this area depends simply on the distance of *p* from *On*.

The area $n\ A\ q\ p$ therefore represents the power supplied to overcome the eddy current losses in the armature of the machine, since these increase in proportion to the square of the speed.

The power spent in overcoming the other losses is represented by the remaining area $A\ O\ m\ q$.

For any given speed the rectangle $A\ O\ m\ q$ may be divided into areas representing the watts spent in the losses due to hysteresis, brush friction, and bearing friction from the results obtained in (*c*), (*d*), and (*e*) above.

The distance between the horizontal lines forming these smaller rectangles is obtained by dividing in each case the number of watts spent in the particular set of losses by the voltage of the dynamo at which the observations were made.

$$\text{Thus amperes (measured vertically)} = \frac{\text{watts lost}}{\text{volts}}$$

Experiment (*b*) will give other lines either above or below AB.

The value of the exciting current which makes the line in the lowest position will be the one giving the lowest armature losses.

It will be found that the hysteresis losses increase rapidly with the strength of field, whereas the frictional losses increase with decrease of field owing to the high speed required to attain the same voltage.

There will consequently be one value of the excitation which will bring the line $A\ B$ into its lowest position, indicating the least amount of loss in the core. This excitation will usually correspond to an induction of about 100,000 lines per square inch in the rim of the armature core. With higher inductions than this the line $A\ B$ is often found to bend upwards, sloping more steeply at higher voltages.

This is due to the demagnetising effect of the eddy currents formed in the armature core and pole faces, and also to the stray field.

The measurements just described are for the determination of very small quantities only. Very small errors of reading are consequently sufficient to produce serious errors in the results. The greatest care must be taken to make the several readings of an experiment under exactly similar conditions.

Thus, for the determination of the internal losses in an armature, slight alteration in the journal friction might be quite sufficient to vitiate the results by the change produced in the power required to drive the armature. In such cases it is found necessary to run the machine for at least an hour before readings are taken, in order to insure that the journal friction has assumed its normal running value, since this normal condition is not attained until the machine has been running continuously for a long period—even when the bearings are provided with the best of lubricating devices.

Also to insure that no alteration has taken place during the experiment, the first reading should be repeated at the end of the series of measurements. If the values then obtained are the same as at first, the conditions may be fairly assumed to have remained constant.

The losses determined in the above experiment occur in the machine with only small armature current. Both eddy current and hysteresis losses increase when the armature carries heavy currents.

Consequently the losses so determined cannot be taken strictly as representing the losses occurring in the machine at full load.

In order to carry out the experiment on a machine with heavy armature current, it is necessary to employ a second dynamo of the same type and size and also a small machine capable of carrying the total current.

The armatures of the three machines are connected in series, and the magnets so excited that one acts as a motor, and one as a generator. The two machines to be tested are mechanically coupled together, and the small machine is driven by an external source, so as to supply the power for keeping the machines in rotation.

With careful adjustment of the exciting current a considerable range of speed may be obtained, while the armature current remains practically constant. The subdivision of the losses is carried out as described above.

Separate Determination of Core Losses.—Another method of measuring the core losses, consisting of hysteresis and eddy current losses, ought to be mentioned.

It consists in running the machine as a motor at a constant speed with various degrees of excitation. The increase in power necessary to drive the armature in a stronger field is a measure of the increased power absorbed in overcoming the armature core losses.

The machine is connected as in Fig. 53, page 160, and run at normal speed and excitation. The current and voltage of the armature are noted. The field is then decreased by increasing the resistance in series with it. The motor will tend to run faster, and the armature voltage must consequently be reduced by increasing the resistance R_1 until the normal speed is again reached. Again the current and voltage of the armature are noted.

A series of readings are taken in this way. In each case the power in watts (=volts × amperes) taken by the armature is calculated. A curve is plotted with watts measured vertically and excitation horizontally. The lower portion of this curve will be nearly straight, and may therefore easily be produced to cut the vertical axis, so as to indicate the number of watts necessary to drive the machine without excitation.

Subtracting the watts corresponding to zero excitation from the watts at any point of the curve, we can form an estimate of the watts actually spent in overcoming the core losses with any degree of field excitation.

In this experiment for the determination of core losses, the importance of maintaining the conditions of measurement absolutely the same, exists as described above. The machine should be run for a considerable time before any measurements are made, so that the bearings may assume their running condition. For insuring accuracy, it is a good plan to repeat the first reading after every measurement.

In this case measurements are made without the full armature current; but as a method of making comparative measurements as to the quality of the material of the core, it is capable of giving valuable results.

Maker's Tests.—Usually dynamos are built to fulfil certain specified conditions as regards heating, capacity to stand overloading, insulation, &c. In some cases these conditions are stipulated for by the purchaser; in other cases the manufacturer applies his own tests to each machine as it is made, and sells the machines with a guarantee that they have passed such tests.

It is usual to subject machines when made, to a test consisting of a six hours' run at full load. If the machine performs the run satisfactorily, the temperature of its armature and field coils is measured and recorded on the completion of the run. A test of the machine is also made in some cases at a load above the normal, perhaps at 25 per cent., or even 50 per cent. overload. Unless specially specified for, this test would usually only last for a short period, say 25 per cent. overload for a half to one hour, and 50 per cent. for a few minutes only, in order to ascertain the behaviour of the machine as regards sparking.

At the conclusion of the test, while the machine is still hot, the resistance of the armature and field windings should be accurately measured and recorded.

The usual methods of determining the temperature of the windings have already been described.

For testing a motor, a special pulley provided with flanges at the edges, and suitable arrangements for maintaining a flow of water round the inside of the rim, is employed. A rope or other suitable brake is applied to the pulley, and a four or six hours' run, to test the heating of the motor, is carried out. Electromagnetic brakes, which have recently been introduced, have already been referred to.

In the case of either a dynamo or motor test, readings are taken at regular intervals (say every five or ten minutes) throughout the run.

These readings should be entered on a form similar to that on page 73 for the dynamo, and on page 129 for the motor. In both cases the final temperature and resistance of both armature and field windings should be added.

As an example of the temperature rise allowable in generators, the following is taken from an Admiralty specification :—

"At the end of a six hours' trial, and one minute after stopping the machine, no accessible part of the armature or field magnet must have a temperature of more than 30° Fah. above that of the dynamo-room, taken on the side of the dynamo remote from the engine, and 3ft. distant from it. Also, the maximum temperature of the armature at the end of the six hours' trial must not exceed the temperature of the dynamo-room by more than 70° Fah."

In carrying out such a test it is usual to read the temperature on mercury thermometers with narrow bulbs, the thermometer bulb being placed against the coil and covered over with cotton wool to prevent radiation. More satisfactory methods have been discussed earlier.

In the case of motors, the rise in temperature which may be allowed depends very largely upon the use to which they are to be put.

In motors likely to run at full load continuously for long periods (motors driving shafting, &c.), a similar specification to that enforced for dynamos should be adopted, say, the maximum rise above the temperature of the room, nor to exceed 40° or 45° C. (*i.e.*, 104° or 113° Fah.) when measured on any accessible part. The internal temperature of the windings will of necessity exceed this limit, as already mentioned.

Motors which are used only for intermittent work (*e.g.*, for cranes, tram cars, hoists, &c.) when tested for one hour at their rated full-load should generally not show a temperature rise exceeding 70° C. (*i.e.*, 158° Fah.), although it would be obviously impossible to lay down a single rule for machines used in a variety of ways.

The Testing of Combined Engine and Dynamo Sets.—In cases where a dynamo is driven by a direct-coupled engine, it is frequently necessary to determine the total efficiency of the combined set consisting of engine and dynamo. The efficiency of such a set should, strictly speaking, be stated as the ratio of the power given out by the dynamo to the power delivered to the engine. It is generally more useful to compare the output of the dynamo with the amount of steam supplied to the steam engine, or with the amount of gas or oil supplied to the gas or oil engine, if they are employed as drivers.

Thus it is usual in the case of a steam-driven plant to specify its efficiency by saying that the consumption of steam is a certain number of pounds per electrical horse-power per hour, or E.H.P. output per hour.

A gas-driven plant would be said to require a given number of cubic feet of gas per electrical horse-power hour.

In the test of a combined steam set, the steam consumption is measured by making measurements of the steam exhausted from the cylinder after condensation. If the steam engine normally works non-condensing, the exhaust steam being intended to escape into the atmosphere, a surface condenser must be provided for the purposes of the test. The steam is then exhausted from the cylinder into the condenser, where it is cooled by the action of a current of cold water flowing through the condenser, but prevented by the condenser walls from mixing with the steam. From the condenser the condensed steam flows into the measuring tanks. The method of measuring the water thus collected from the condenser will depend on the duration of the test.

If the test is only of short duration, it will probably be convenient to collect all the condensed water in a tank, and measure the total amount after the conclusion of the test.

If the test is to be a long one, it would be inconvenient to employ a tank large enough to hold all the water used, and a method of measuring the water continuously should be adopted. For this purpose a water meter may be used, but such instruments, besides being somewhat costly, are very liable to create considerable errors.

The most accurate method of measuring the condensed water is to weigh it. To do this continuously necessitates the use of two tanks, the first discharging into the second, which is mounted on the bed of a weighing machine. As the second tank becomes full it is shut off from the first tank; the weight of its contents is noted, and the water then emptied away. After this the tank is again allowed to fill from the first one. By suitably arranging the position of the tanks, the first over the second, and providing them with cocks, this process may be made to work with very little trouble.

The process of weighing may be avoided if the capacity of the tanks into which the water is run has been previously determined, or, better still, if the measuring tank has been experimentally graduated and a scale marked on the inside of the tank, or on a glass gauge fixed outside, the divisions of the scale corresponding to pounds of water.

If the measurement is to be made continuously for a long period, it is convenient to employ two tanks, into which the condenser discharges alternately.

A very simple and convenient arrangement of this kind is to divide a rectangular tank into two compartments by a vertical plate, not quite equal in height to the sides of the tank. Each compartment of the tank is graduated separately, and is provided with a glass gauge and scale. The condensed steam is delivered to the tank by a pipe fitted with a short piece of rubber tube. By displacing the free end of the rubber tube to the right or left the pipe can be made to discharge into either compartment of the tank. A plug cock is fitted to each compartment to allow of its being emptied. Both cocks deliver into a tank below the measuring tank, from which the feed water for the boiler may be drawn.

The division between the compartments of the measuring tank does not reach quite to the top of the tank, so that if the observer should omit to switch over when one compartment is full, the condensed steam will simply flow over the top of the diaphragm into the other compartment, and be measured in that compartment.

If the temperature of the water flowing into the measuring tank is much different from the temperature of the water employed in calibrating the tank, a correction must be made to allow for the alteration in volume of the heated water.

Where frequent tests are made, the tank is often arranged on the platform of a lever weighing machine. A special provision may be made for the ringing of an electric bell as soon as the weight of water in the tank is sufficient to raise the weighted lever of the machine. In measuring the steam consumption the weight on the beam is moved along until it overbalances the water in the tank. As the tank fills the beam rises and causes the electric bell to ring, and the observer then notes the exact time on a clock conveniently placed. He sets the weight farther along the beam by a certain amount, varying from 10lbs. to 300lbs., according to the size of the engine and its load, so that the bell will ring again after some convenient number of minutes. By this means the steam consumption of the engine throughout the test can be continuously recorded.

If the engine is of the condensing type, the condenser air pump may be arranged to deliver the condensed steam directly into the measuring tank, or the measuring tank may be put into communication with the hot-well, and measure the water received by the hot-well from the condenser.

Steam should, if possible, always be supplied to the engine through a separator, to prevent condensed water entering the cylinder with the steam. The consumption of an engine is supposed to be stated in pounds of dry steam.

The electrical output is measured by making observations at regular intervals (say every minute for a test extending over about half an hour, or every five minutes for a more extended test) of the voltage and current of the dynamo.

The electrical connections required are as follows: If the dynamo is shunt wound, the magnet windings must be connected to the dynamo terminals in series with an adjustable shunt regulating resistance for keeping the main voltage constant, and correcting for the alteration in resistance of the shunt coils as they become heated. If the dynamo is compound wound, the series winding must be connected in series with the main external circuit of the machine.

The load is applied by connecting the resistances, which are to absorb the energy, to the dynamo terminals, an ammeter being included in the circuit. A voltmeter is also connected to the terminals for reading the voltage generated.

Diagrams of the necessary connections are shown—

In Fig. 22, page 71, for a shunt dynamo.
In Fig. 34, page 97, for a compound dynamo.
In Fig. 27, page 81, for a series dynamo.

It is desirable also to measure the exciting current and field voltage during the test.

It is usual to conduct tests at several values of the load, say, at quarter, half, three-quarters, and full load, since the efficiency at light loads will be less than at full load.

The pressure of steam is read on a gauge communicating with the engine steam chest, since the pressure there is the pressure actually received by the engine.

The form for entering the results of such a test is as follows:—

Experiment XXI.—Steam Consumption Test of Combined Engine and Dynamo Set.

RESULTS OF TEST AT .... LOAD.

Observers ....Date ....
Engine No. ....Type ....
Dynamo No..........................Type ....
Normal Output............Volts......Amps. at......revs. per min.

Time.	Lbs. of Water Collected.	Pressure in Steam Chest.	Revolutions per minute.	Output of Dynamo.		Field Excitation.		Remarks.
				Volts.	Amps.	Volts.	Amps.	

Engine working (condensing or non-condensing.)
Cut-off in cylinder at ....of stroke.

A series of readings are taken and entered on the above form for each value of the load for which it is desired to test the steam consumption.

The mean values of the quantities entered in the columns are then determined for each set of readings, and the results of the test summarised on the following table, the general heading being the same as for the previous table.

Summary of Steam Consumption Test.

Load.	Pressure in Steam Chest.	Revolutions per minute.	Volts.	Amperes.	Kilowatts.	E.H.P.	Lbs. of Steam per hour.	Lbs. of Steam per E.H.P. per hour.	Lbs. of Steam per Kw. per hour.

In the above table the "lbs. of steam per hour" means the rate at which steam is supplied to the engine measured in pounds per hour. It is obtained by dividing the weight of steam condensed by the duration of the trial in minutes and multiplying this result by 60.

The last two columns are obtained by dividing the figures in the column "lbs. of steam per hour" by the corresponding figures in the columns headed "E.H.P." and "Kilowatts."

The test is rendered more complete if the indicated horse-power of the engine is determined by a few indicator diagrams taken at equal intervals during each test. From these diagrams the mean pressure in the cylinder and the actual power exerted by the steam on the piston can be calculated.

Frequently a brake test of the engine alone is also made, so that the losses occurring in the engine and dynamo can be separated.

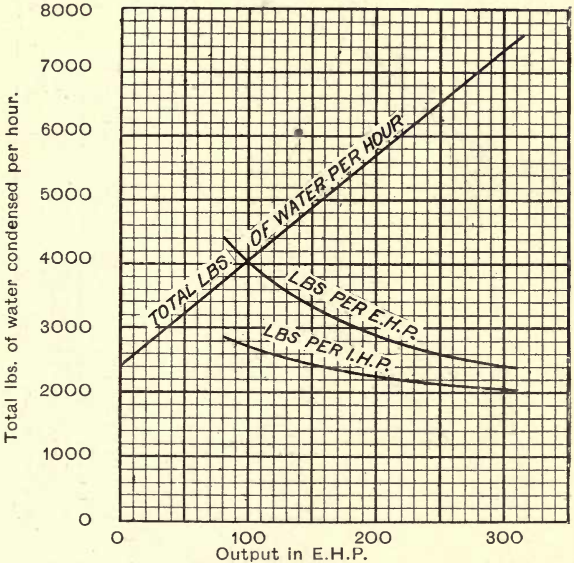

FIG. 56.—STEAM CONSUMPTION TEST OF COMBINED PLANT.

The final table of results then assumes the following form, the general heading again being as before:—

Summary of Steam Consumption Test.

Load.	Pressure in Steam Chest.	Cut Off.	Mean Pressure.	Vacuum in Condenser.	Revolutions per minute.	I.H.P.	B.H.P.	E.H.P.	Steam Consumption in lbs. per hour.			Efficiency=$\frac{\text{H.P. Output}}{\text{I.H.P.}}$	
									Per I.H.P.	Per B.H.P.	Per E H.P.	$\frac{\text{B.H.P.}}{\text{I.H.P.}}$	$\frac{\text{E.H.P.}}{\text{I.H.P.}}$

In Fig. 56 are given three curves, showing graphically the result of a steam consumption test of a Willans-Siemens set. The engine was compound, of 360 h.p., working without condensation.

The upper straight line shows that the steam consumption increased in direct proportion to the electric output. This is, as a general rule, found to be the case in steam trials.

The two lower curves show how the consumption per electrical horse-power and per indicated horse-power decrease with an increased load on the engine. These curves should, of course, always slope downwards, showing an increased efficiency of the set at higher loads.

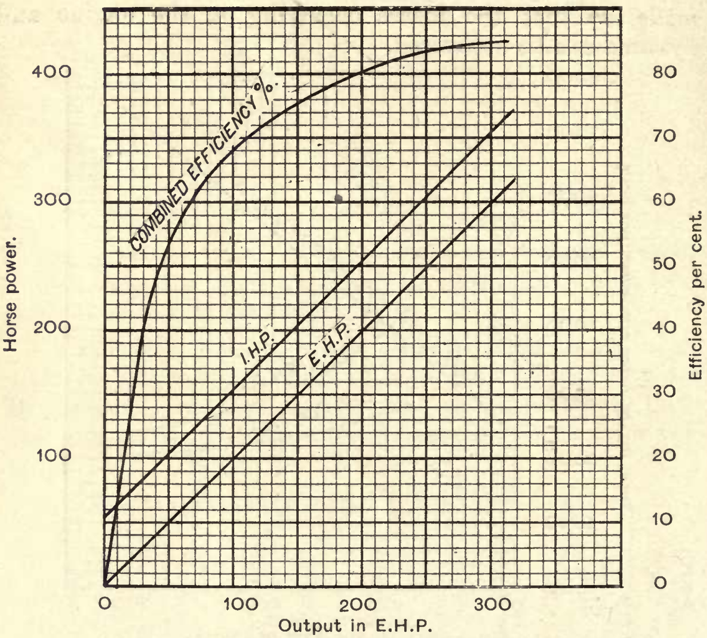

FIG. 57.—EFFICIENCY TEST OF COMBINED PLANT.

The upper two curves in Fig. 57 apply to the same test, and show the combined efficiency at various loads, and also the indicated horse-power compared with electrical output. The lower straight line is added for comparison with the indicated horse-power line, the distance measured vertically between the two giving the power spent in overcoming frictional and analogous losses occurring in the engine and dynamo.

The lines in this case are apparently parallel. In reality they must diverge slightly for increased values of the output, since the losses in the journals, and the electrical losses in the armature conductors, and those due to eddy currents, must increase slightly with the load, although this increase will generally be only slight at constant speed.

CHAPTER XII.

MISCELLANEOUS TESTS.

Insulation Tests.—There are two distinct properties which the insulation of a completed machine should possess.

Firstly, the ability to withstand the application of a high voltage for a long time without deterioration. This is the *dielectric strength* of the insulation.

Secondly, the insulation must offer a sufficiently high resistance to prevent any appreciable leakage in working. That is, its *insulation resistance* must be high. These two properties are not necessarily to be found together in insulating materials.

The insulation of a dynamo or motor should first be tested by the application of an alternating voltage 5 to 10 times the working pressure of the machine, applied between one of the main terminals and the frame. This test is to make sure that all conductors are insulated from the iron portions of the machine, which are frequently uninsulated from the earth.

After this test of the dielectric strength of the insulation, that is, its strength to withstand the breaking down strain of a high voltage, the insulation resistance should be measured. This should be done both when cold and when the machine is heated by a run.

The insulation test may be made by any of the usual testing sets, such as the Silvertown or Siemens' insulation testing set. A usual method is to use a battery of cells giving a pressure of about 200 volts, connected in series with the insulation resistance to be measured, and with a sensitive galvanometer of which the constant is known. Any leakage which takes place through the insulation will deflect the galvanometer. The amount of leakage current corresponding to the galvanometer deflection is calculated from the constant of the instrument. The resistance in the circuit is given by dividing the voltage of the battery by this current. Subtracting the galvanometer resistance, the insulation resistance is obtained.

The following is a simple method not requiring the use of any special apparatus beyond a voltmeter, and applicable while the machine is at work. It is specially suitable as a periodic test to be applied to motors and dynamos while in continued use.

This method is frequently used in testing the insulation resistance of the conductors of an installation. In such a case the connections are made from the conductors to a well "earthed" metal object, such as the water or gas pipes. The bed of a dynamo is sometimes entirely or partially insulated from the earth.

Experiment XXII.—DETERMINATION OF THE INSULATION RESISTANCE OF A DYNAMO WHILE RUNNING.

Instructions.—Connect the terminals of a voltmeter respectively to one terminal of the dynamo and to any convenient point on the frame. Note the voltmeter reading.

Take a second reading with the voltmeter connected to the other terminal of the machine and to the frame.

Read the voltage between the machine terminals.

The joint insulation resistance between the windings and the frame is given by the formula.

$$R = \left\{ \frac{V}{V_1 + V_2} - 1 \right\} G$$

where the symbols have the following signification :—

A B the two terminals. (See Fig. 58, page 184.)
F the frame.
R_1 R_2 insulation resistance between the respective terminals and the frame.
V_1; V_2 readings of the voltmeter when connected with the frame and A and B respectively.
V voltage measured between A and B.
G resistance of voltmeter.
R combined insulation resistance of windings from the frame.

$$= \frac{1}{\frac{1}{R_1} + \frac{1}{R_2}}$$

Calculation.—The leakage current flows from one pole of the machine to the other, passing first from the + pole to the frame, and then from the frame to the − pole.

The algebraical sum of the currents flowing to the frame from the conductors connected to the two poles of the machine will therefore always be zero.

Hence when the voltmeter is connected to A, the sum of the currents flowing to and from the frame

$$= \frac{V_1}{R_2} + \frac{V_1}{G} + \frac{V_1 - V}{R_1} = 0$$

and when the voltmeter is connected to B, the currents flowing are

$$\frac{V_2}{R_1} + \frac{V_2}{G} + \frac{V_2 - V}{R_2} = 0$$

Adding these equations :

$$V_1\left(\frac{1}{R_1} + \frac{1}{R_2}\right) + V_2\left(\frac{1}{R_1} + \frac{1}{R_2}\right) - V\left(\frac{1}{R_1} + \frac{1}{R_2}\right) + \frac{V_1 + V_2}{G} = 0$$

that is, since $R = \dfrac{1}{\dfrac{1}{R_1} + \dfrac{1}{R_2}}$

$$\frac{1}{R}(V_1 + V_2 - V) + \frac{V_1 + V_2}{G} = 0$$

or $R = \left(\dfrac{V}{V_1 + V_2} - 1\right) G$ as given above.

NOTE.—The voltmeter employed should have approximately the same resistance as that of the insulation to be measured in order to get the maximum sensitiveness.

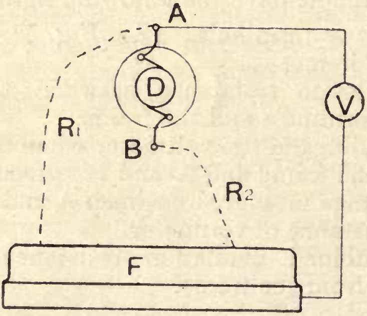

FIG. 58.—MEASUREMENT OF INSULATION RESISTANCE.

Magnetic Leakage.—A certain proportion of the magnetic lines produced by the magnet windings of a dynamo or motor do not follow the iron magnetic circuit of the machine, but "leak" across from one part of the circuit to another through the air. Many of these lines do not pass through the armature core, and are consequently without effect upon the voltage or output of the machine. The lines of force which do not pass through the armature form what is called the "stray field."

The magnetic leakage between any two points of the magnetic circuit depends on the relative magnetic resistance of the path formed by the magnetic circuit, and the "leakage path" through the air or any iron situated in the neighbourhood. Consequently there will usually be considerable leakage between surfaces only a small distance apart.

In some types of two-pole dynamos, for instance, the distance apart of the inner faces of the magnet limbs is small, whereas the iron portion of the magnetic circuit joining the limbs through the yoke is of considerable length, and consequently a number of lines pass across the air space between the limbs instead of through the iron yoke. If the yoke is of insufficient section the number of leakage lines will be increased.

The magnetising force of the magnet windings must be sufficient to produce the required strength of field through the armature, as well as the lines of the stray field which are not cut by the armature conductors.

The object of the following experiment is to determine what proportion of lines of force in the magnetic circuit of a dynamo or motor do not pass through the armature, and do not therefore contribute to the voltage of the machine, but form the "stray field."

The proportion of the total number of lines formed to the number which pass through the armature is known as the "leakage coefficient" of the machine.

Experiment XXIII.—DETERMINATION OF THE LEAKAGE COEFFICIENT OF THE MAGNETIC CIRCUIT OF A DYNAMO OR MOTOR.

Connections.—Wind a small number of turns of insulated wire round the centre of one magnet limb of the machine. The best number of turns will depend on the size of the magnet and the sensitiveness of the galvanometer—usually between 2 and 10 turns should be sufficient. The wire should be wound closely round the magnet, and the ends brought out and twisted together to prevent stray lines from affecting the deflection.

Connect the ends of this winding to a ballistic galvanometer, putting a non-inductive resistance in series with the galvanometer, if necessary, to prevent the deflections being too large.

The galvanometer should be at a considerable distance from the machine being tested, to prevent its being affected by the stray field.

Connect the field windings to a source of current through a switch, including, if necessary, a resistance to reduce the current to the value of the normal exciting current of the machine.

Instructions.—Close the switch in the magnetising circuit suddenly, and note the galvanometer throw (*i.e*, the furthest point to which the needle swings).

After the needle has returned to rest, open the switch rapidly, and again note the throw.

Take similar readings several times with the exploring coil in the same position on the magnet.

Then repeat the readings with the coil, or an equal number of turns of wire, situated successively at each end of the magnet limbs, round the yoke and round the armature, as nearly as possible in the plane of the shaft perpendicular to the axis of the field.

The difference between the greatest and least deflection obtained with the coil in different positions will give approximately the proportion of leakage lines. The least deflection will be obtained with the coil wound round the armature core.

Enter results thus :—

DETERMINATION OF LEAKAGE COEFFICIENT OF A DYNAMO.

Observer................................. Date..

Dynamo No.......................... Type..

Normal output...........amps............volts, at..............revs. per min.

Position of Coil.	Armature current.	Exciting current.	Galvanometer Deflections.			Coefficient of Leakage $= \frac{\text{Max. deflect'n}}{\text{Min. deflect'n.}}$
			On Making.	On Breaking.	Mean.	

The test should be carried out with various degrees of saturation of the field, and also with the armature of the machine carrying its full load current supplied from an external source. The leakage increases at heavy loads, on account of the magnetic reactions of the armature, especially when the brushes are given a considerable angle of forward lead. The armature should be held stationary, or it will rotate on "making" the field.

It is extremely difficult to get exact results by any ballistic method such as that described above. Consequently, it would be unwise to base any calculation of the *actual number* of lines of force in the field upon the result of such a test. If carried out carefully with sufficient precautions to maintain uniform conditions during the experiment, the test may safely be taken as giving the *relative number* of lines in different parts of the magnetic circuit. If it is desired to calculate from experiment the *actual number* of lines, this should be done as described in Experiment IV., page 26.

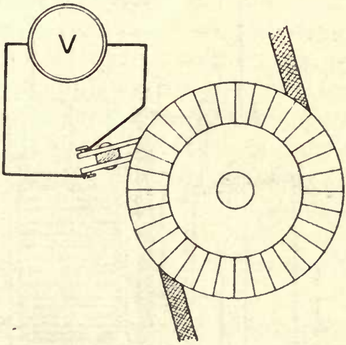

FIG. 59.—METHOD OF MEASURING VOLTAGE ROUND THE COMMUTATOR.

DETERMINATION OF VOLTAGE ROUND THE ARMATURE.

General Description.—A completely different method of investigating the actions occurring in the armature from any of those previously discussed, is to measure the voltage induced in the coils connected between individual pairs of commutator segments at different points in their rotation. This is done by small auxiliary brushes, which can be made to make contact with the commutator at any angle, making it possible to determine, by means of a voltmeter, the voltage generated in any portion of the armature.

There are two principal methods of making a complete measurement of the voltage generated between each pair of commutator segments. One method is to use two small brushes insulated from each other, and fixed at a distance apart equal to the distance between two segments. By moving the carrier supporting these brushes round, so as to enable them to make contact at a succession of points round the commutator, the electromotive force induced in the conductors at any point of the revolution may be read off on a low-reading voltmeter connected to the auxiliary brushes. The method is indicated in Fig. 59.*

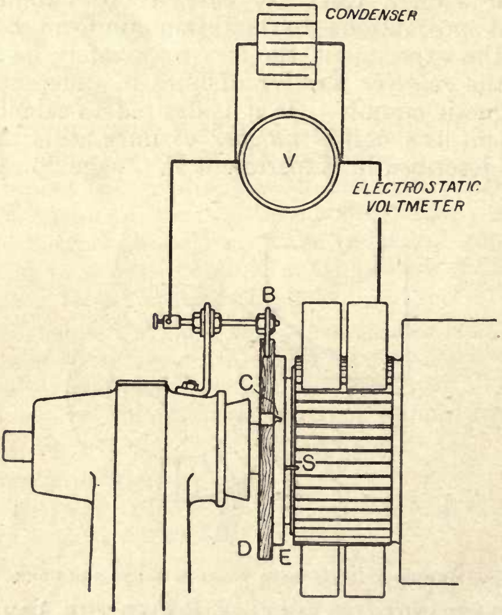

Fig. 60.—Method of Testing Voltage Round Commutator.

The other method (see Fig. 60) consists in having a single exploring brush only, which may be brought into any position on the commutator. The difference in voltage between one of the main brushes of the machine and the exploring brush, when moved into various positions, is then read upon a voltmeter. By taking a

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* The readings of the voltmeter will be slightly lower than the actual difference in voltage between the segments, owing to the fact that in passing from one segment to another the brushes will be short-circuited for an instant.

succession of readings, the exploring brush being moved away from the main brush by a distance equal to the width of one segment between each reading, an increase of electromotive force equal to that generated in the conductors connected to one pair of segments is added to the voltmeter reading each time.

The use of the pair of exploring brushes has the advantage that the readings of the voltmeter vary to a less extent, since they never exceed the voltage between one pair of segments. In the second arrangement, with a single pilot brush, the voltage to be read varies from zero to the full voltage of the machine. This necessitates the use of a voltmeter, or voltmeters, having a very wide range of sensitiveness.

Whichever method is adopted, the mode of procedure is much the same. The auxiliary brush must be arranged so as to be capable of moving the point of contact round the commutator from the positive to the next negative brush. This will be a range of a complete semicircle in the case of a 2-pole dynamo. A dial should be attached to the machine divided into degrees, or, preferably, into divisions corresponding to the commutator segments, so that the movement given to the brush holder can be easily adjusted. Usually the most convenient attachment consists in a slotted semicircular casting of brass, which can be screwed on to the side of the field magnets. The exploring brush is then fixed to a stud provided with a curved head fitting into the slot of the casting, a clamping nut serving to fix it in position.

In dynamos made specially for experimental work, a special attachment is sometimes provided, fixed to the bearing of the machine.

Another method of altering the point of contact is shown in outline in Fig. 60. This is simple to fix, but generally necessitates the use of an electrostatic voltmeter or electrometer, instead of a voltmeter of the more common moving-coil or electro-magnetic types. This is owing to the fact that the voltage to be measured is only applied to the instrument intermittently, just at the moment when the brush B touches the metal strip C, that is, once during a revolution. This would either cause an ordinary voltmeter needle to oscillate rapidly, or else (if the voltmeter were sufficiently dead-beat) to take up some mean position lower than that corresponding to the voltage applied during the instant of contact.

As an alternative to the electrostatic voltmeter, a condenser which is charged or discharged through a ballistic galvanometer may be used. The galvanometer must be calibrated by charging the condenser from a source of known voltage, and discharging through the galvanometer. If the throws of the galvanometer needle are small, voltages may be taken as proportional to the throw. If the galvanometer needle swings through a considerable angle, the voltage must be taken as proportional to the sine of half the angle of the throw.†

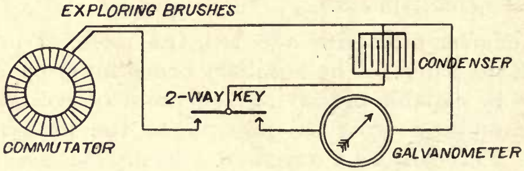

FIG. 61.—METHOD OF MEASURING VOLTAGE ROUND THE COMMUTATOR.

The connections necessary for alternately charging and discharging the condenser are indicated in Fig. 61. The 2-way key should remain in the position for charging the condenser except when a reading is to be made. A Morse telegraph key answers very well for the purpose.

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† For example, suppose that when a condenser, charged from cells to a voltage V, is discharged through the galvanometer, it is found to give a throw of a millimetres on a scale fixed at a distance of r millimetres from the galvanometer. The angle of deflection measured in circular measure $= \frac{\text{arc}}{\text{radius}} = \frac{a}{r}$, since, for all practical purposes, the scale may be taken to form part of the circumference of a circle of which the galvanometer is the centre.

Suppose that the condenser is then charged from the exploring brushes of the machine, and, on being discharged through the galvanometer, the deflection is a'.

Then the second voltage V' is given by the proportion

$$\frac{V}{V'} = \frac{\sin \frac{a}{4r}}{\sin \frac{a'}{4r}}.$$

$$\text{or } V' = \frac{\sin \frac{a'}{4r}}{\sin \frac{a}{4r}} V.$$

The factor $4r$ in the denominator occurs in the case of a reflecting galvanometer instead of $2r$, because the angle moved through by the spot of light, which serves as the index, is twice the angle moved through by the mirror itself.

In the arrangement of contacts shown in Fig. 60, the brush B is fixed, and makes contact with a metal strip C let into the edge of a disc D of wood or other insulating material, which rotates with the shaft of the machine. The metal contact strip C is in metallic connection with a small metal spring S which presses on one segment of the commutator.

Hence, once during each revolution of the commutator this segment is connected to one pole of the voltmeter, while one of the main brushes is permanently connected with the other pole. The voltmeter consequently reads the difference of potential between the main brush and the segment in contact with the spring. By arranging that the position of the segment contact S may be placed at any angle relative to the contact C, the difference of potential corresponding to any position of the segment may be obtained.

The particular arrangement sketched in Fig. 60 is very easy to fit up. The rotating portion consists of two discs of wood D and E which can be rotated relatively to each other and fixed together in any position by a couple of screws moving in a circular slot. One of the discs is fixed to the shaft; the other disc is carried round by it. The disc D has a contact piece C let into one point of its rim. This contact has a tongue which makes contact with the continuous metal rim with which the other disc E is provided. The metallic rim of E is connected to a small spring S, which presses upon the commutator. By moving the discs relatively to each other, the position of the segment, which is put momentarily in contact with the voltmeter through the brush B, can be varied as desired.

A condenser will be seen in Fig. 60 connected in parallel with the voltmeter. This will usually be found necessary in order to get a steady reading on the voltmeter—indeed, many voltmeters will not give a reading at all without the condenser, the voltmeter being of so small a capacity that it discharges itself too rapidly to affect the slow-moving needle.

Experiment XXIV.—DETERMINATION OF VOLTAGE CURVE ROUND THE COMMUTATOR.—From what has been said above, the method of carrying out the measurements ought to be clear. The exact connections and course to be adopted depend so much on the nature of the apparatus employed, that complete instructions as to connections and readings cannot be given.

Connect the contact maker to a voltmeter of suitable range. If the voltage between consecutive segments only is being measured, the voltmeter need have only a low range of readings. The position of the contact should be moved forward by the exact angle corresponding to one commutator segment between each reading.

If it is easy to stop and restart the machine, this may be most easily done by stopping the machine and adjusting the position of the armature until the tip of the brushes coincides with the division between two commutator segments, then moving the brushes forward by the width of one segment.

Connect the main dynamo terminals to another voltmeter. By means of an adjustable field regulating resistance maintain the readings of this voltmeter constant, to insure that all readings are taken while the dynamo is giving the same voltage. If the dynamo voltage cannot be kept constant, a proportional correction must be made in the readings.

Take a series of readings while the machine is giving no current. Then take a similar series of observations with the machine giving out its full-load current, in order to ascertain the effect of the armature current upon the field distribution.

The table on the following page shows the method of recording the readings.

In this and in similar experiments considerable errors may be introduced by the contact resistance of the auxiliary brushes connected to the voltmeter.

If the contact surfaces are not quite clean, or the vibration due to the rotation of the commutator is sufficient to make the contact uncertain, the readings of the voltmeter will not be reliable. This can sometimes be detected by merely pressing the brush rather harder on to the commutator, and observing whether the voltmeter deflection is affected.

DETERMINATION OF VOLTAGE CURVE ROUND THE COMMUTATOR.

Observer .... Date ....
Dynamo No. .... Type ....
Normal output........amps.,......volts., at........revs. per minute.
Terminal voltage during experiment...............
Speed...
Armature current ....

No. of Segment from......brush.	Volts.	
	Voltmeter No.	
	Constant.	
	Reading.	True Value.

A method by which this source of error is avoided is to use a potentiometer for determining the voltage instead of a voltmeter. When the drop in the potentiometer wire is balanced against the voltage to be measured, and the reading is being taken, no current is taken from the contact brush, and consequently variations of contact resistance do not affect the reading.

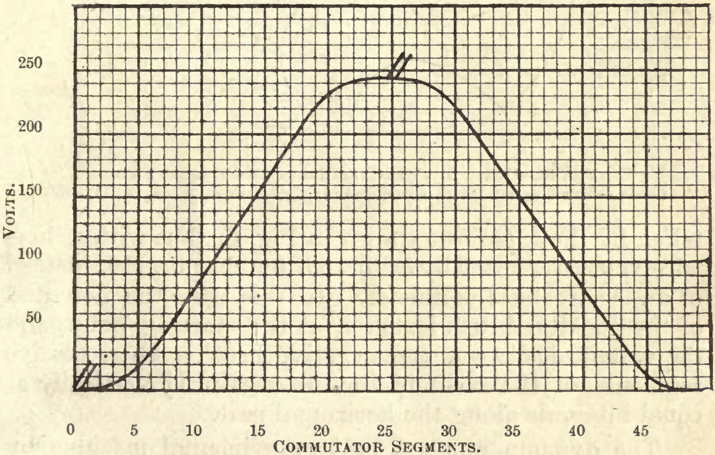

FIG. 62.—CURVE OF VOLTAGE ROUND COMMUTATOR.

Variations of this device may be employed, such as connecting the brushes to a uniform stretched wire, and determining the length of this wire, which will balance a cell of known voltage, and so produce no deflection on a galvanometer joined in series with the cell and a portion of the wire. This method does not, however, avoid errors due to contact resistance.

Plotting Results.—The readings obtained in the preceding experiment should be shown graphically on a curve. This may be done in either of two ways. Fig. 62 shows the results of a test plotted according to the method which it is preferable to adopt, the readings being taken by the apparatus shown in Fig. 60, but with a hot-wire voltmeter specially calibrated for the purpose, instead of an electrostatic voltmeter. In this case the potential of the negative brush is taken as the starting point, and the voltages between the negative brush and successive segments of the commutator are measured vertically at equal intervals along the horizontal scale.

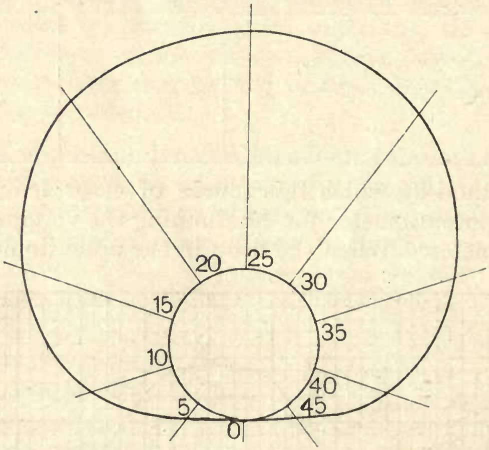

FIG. 63.—CURVE OF POTENTIAL ROUND THE COMMUTATOR.
(NOTE.—This diagram is not reproduced exactly to the same scale as Fig. 62.)

The dynamo was a 2-pole experimental machine by Schuckert, and was giving no load. The brushes were without lead, and the curve is consequently nearly symmetrical. It shows, in fact, the distribution of voltage in the armature when not disturbed by armature reactions.

Figs. 63 and 64 show two other ways of plotting the results of the same experiment.

In Fig. 63 a circle of any convenient size is drawn to represent the commutator. The position of the negative brush is again taken as the starting point, and the measured voltages are measured radially from the circumference of the circle at the angles at which they were actually measured.

Fig. 64 shows the same results plotted so as to give the difference of potential between successive pairs of segments, instead of the potential between the segments and the negative brush. When plotting results in this way the position of the poles of the dynamo should always be indicated, as well as the position of the brushes.

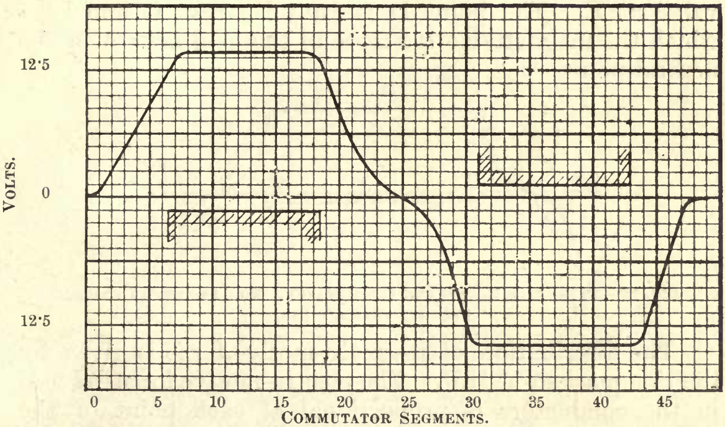

FIG. 64.—CURVE OF VOLTAGE ROUND COMMUTATOR.

In order to explain the significance of curves such as that shown in Fig. 64, it will be useful to refer to a series of curves obtained theoretically by Mr. C. P. Steinmetz.*

The distribution of magnetic flux at the surface of the armature core can be calculated approximately by assuming that the density at any point of the surface is proportional to the acting magneto-motive force, and inversely proportional to the distance from the nearest magnet pole. Thus, if N C = ampere-turns producing the flux between armature and pole face, a = length of air gap from iron of the pole face to iron of the armature core, then the magnetic density under the magnet pole, that is, between B and C (Fig. 65), is

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* "Theoretical Elements of Electrical Engineering." New York: *Electrical World and Engineer.*

$H = \frac{4\,\pi NC}{10\,a}$ lines per square centimetre. (See page 34.)

At a point on the armature surface at a distance x from the end of the pole, the distance from the pole tip is $d = \sqrt{a^2 + x^2}$ The magnetic density at this point is consequently

$$H = \frac{4\,\pi NC}{10\sqrt{a^2 + x^2}}$$

The magneto-motive force is constant only under each field pole, but decreases between the poles from C to E in Fig. 65 from the full value at C to the full opposite value at E. The point D midway between C and E at which the magneto-motive force of the field is zero is the neutral point.

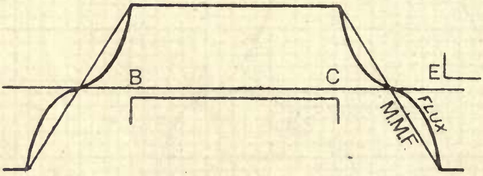

Fig. 65.—Potential Round the Commutator. No Armature Current. Brushes without Lead.

The distribution of magneto-motive force is given by the line marked M.M.F. The electro-motive force induced in the conductors is proportional at each point of the revolution to the magnetic flux. Thus the curve marked "flux" in the Figures 65 to 69 may be taken to represent also the variation of electro-motive force round the commutator.

The curve given in Fig. 65 marked "flux" was calculated and plotted according to the above assumptions. The values assumed were :—

$$a = 1\,;\quad H = 8{,}000\,;\quad N\,C = 6{,}400.$$

The flux passes through a zero point midway between the poles.

This distribution of magnetic flux applies only when the armature carries no current, and corresponds to the experimentally-determined curve in Fig. 64. With a load current the magneto-motive force of the armature affects the magneto-motive force due to the main field windings.

First, suppose the brushes set at D and G (Fig. 66) midway between the pole tips. The maximum magneto-motive force due to the armature current will be experienced along the axis joining the conductors connected to the brushes. The field due to armature reaction will therefore be greatest at D and G, acting in opposite directions at these points, and decreasing gradually between them. In Fig. 66 the line marked M.M.F. represents the variation of the magneto-motive force due to the main field, as before, while the line m.m.f. shows that due to the armature current.

The flux due to the algebraic sum of the magneto-motive forces is shown by the line "flux."

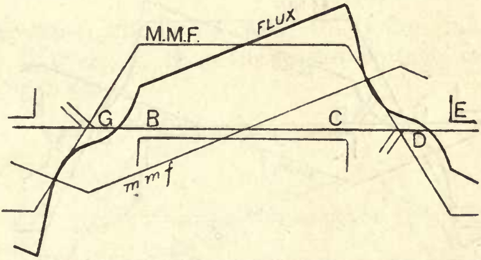

FIG. 66.—POTENTIAL ROUND COMMUTATOR, WITH CURRENT IN ARMATURE. BRUSHES WITHOUT LEAD. SATURATION OF POLES NEGLECTED.

The effect of the armature reaction is to strengthen the field under the right hand, or "leading" pole tip, and to weaken it under the left hand or "trailing" tip. If the brushes are situated midway between the poles, the strengthening and weakening effects will be equal, and consequently the total flux (neglecting the effect of saturation to be presently considered) remains unaltered. The voltage of the dynamo should therefore be unaffected by the load, except for the volts "lost" in the resistance of the armature conductors. Armature reaction with the brushes midway between the poles distorts the field, but neither tends to magnetise or demagnetise the poles when they are below the point of saturation.

The distortion of the main field is due to the current flowing in the conductors situated on the armature immediately under the poles, *i.e.*, between B and C in Fig. 66.

Thus if $v =$ polar arc, or the angle covered by the pole face (two poles and the arc between them or one complete cycle being denoted by 360°), the ampere-turns producing distortion will be $\frac{v.n.c.}{180}$, where n represents the number of conductors on the armature per pole and c is the armature current.

In Fig. 66 the ratio $\frac{\text{main field ampere-turns}}{\text{armature reactive ampere-turns}}$ is assumed to be $\frac{4}{3}$ and the resultant strength of field (and consequently the voltage induced in conductors at those points) at the opposite pole tips is in the proportion of 1 to 3.

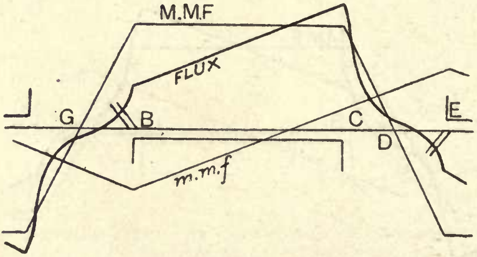

FIG. 67.—POTENTIAL ROUND COMMUTATOR. CURRENT IN ARMATURE. BRUSHES WITH LEAD. SATURATION OF POLES NEGLECTED.

As may be seen, the mean electro-motive force induced is not changed by the armature reaction. At D the coils passing under the brush will be still active, and will produce sparking, as they are short-circuited by the contact of the brush with two adjacent segments of the commutator. Hence, under load the brushes must be shifted forward. On account of the self-induction in the coils when carrying current, the brushes must be moved forward beyond the point corresponding to no induction, so far that the field due to the next pole provides sufficient counter electro-motive force to counteract the electromotive force of self-induction due to the current in the coils, which are short-circuited.

In Fig. 67 the brushes are shown moved forward until they are under the tip of the next pole. The line showing the magneto-motive force due to the armature current is moved forward by the same amount, and the flux represented by it weakens the main field more than it strengthens it. The total flux through the armature is therefore decreased. That is, with brushes having lead, the armature reaction demagnetises the field.

If h is the angular lead given to the brushes = G B in Fig. 67, then the demagnetising component of the armature reaction is $\frac{2hnc}{180}$ and the component which produces distortion only is $\frac{vnc}{180}$ as before.

Thus, with shifted brushes, the full excitation must be increased under load in order to maintain the original voltage. Accordingly Fig. 67 is drawn with the full excitation increased by the fraction $\frac{2hnc}{180}$ ($= \frac{nc}{3}$ for this particular case), compared with the value taken in the previous figures, so that the mean voltage may be the same in each case.

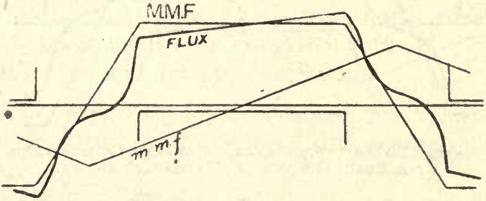

Fig. 68.—Potential Round Commutator. Current in Armature. Brushes without Lead. Effect of Saturation Shown.

In the Figures 65 to 67 the effect of magnetic saturation has been neglected. It was assumed that the magnetic density in the iron near the air gap increased or decreased in the same proportion as the magnetising force.

The distribution of the magnetising force is unaffected by saturation, but the distribution of magnetic flux is materially altered.

To illustrate the effect of saturation, Figs. 68 and 69 have been drawn with an air gap of one-half its value in Figs. 65 to 67. The air gap thus absorbs only one-half the number of ampere-turns which it did in the previous case. The other half of the ampere-turns is assumed to be required in order to send the required magnetic flux through the saturated armature teeth.

In Figs. 68 and 69, which correspond in other respects with Figs. 66 and 67, the effect of saturation is seen. The magnetic induction is spread further at the pole corners, the general effect being to make the curve of voltage more uniform.

The demagnetising effect of the load due to the lead of the brushes is hardly changed. The distorting effect of armature reaction is greatly decreased, being only a small percentage of its previous value, and the magnetic field under the pole is made nearly uniform at any load.

The reason is that even a large increase or decrease of magnetising force does not materially alter the total flux, the added or subtracted ampere-turns producing but little effect on the saturated iron.

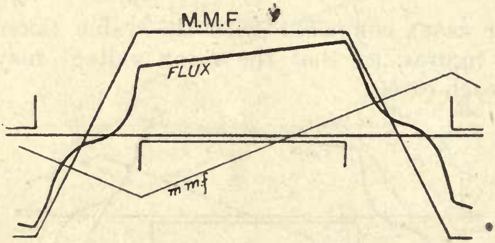

FIG. 69.—POTENTIAL ROUND COMMUTATOR. CURRENT IN ARMATURE. BRUSHES WITH LEAD. EFFECT OF SATURATION SHOWN.

Thus, while in Fig. 67 the densities are 8,000 at the centre and 12,000 and 4,000 at the tips of the poles, with the saturated core in Fig. 69 the densities are 8,000, 9,040, and 6,550 respectively.

Thus the saturation of the armature teeth or of the pole face (in particular the tips) affords a means of reducing the distortion of the magnetic field, and the variation of the field under the pole tips. It is consequently advantageous for machines which have to operate with widely varying loads, and with brushes in a fixed position.

In the case of a motor, the current in the armature flows in the opposite direction to that in a dynamo with the same field. The direction of the armature reactive field will therefore be in the opposite direction.

Consequently, in order to obtain sparkless running, the brushes should be given a *backward* lead, so as to bring the conductors which are short circuited by the brushes under the influence of the opposite pole. Consequently, it is the field of the *trailing* pole tips which is strengthened by the armature currents in the case of a motor. The curve of electro-motive force drawn in the manner just discussed will consequently slope in opposite directions for a generator and a motor.

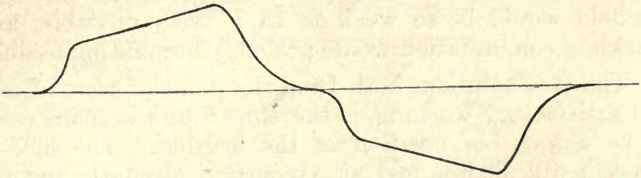

FIG. 70.—CURVE OF POTENTIAL ROUND THE COMMUTATOR. MACHINE WORKING AS GENERATOR.

To illustrate this, the curves shown in Figs. 70 and 71 (both taken from the same machine) have been drawn. Fig. 70 is the curve obtained when the machine was supplying current. Fig. 71 shows a curve obtained from the same machine when supplied with current from an external source and acting as a motor.

Such curves as those given above are very valuable as a means of testing the effect of different shapes of pole

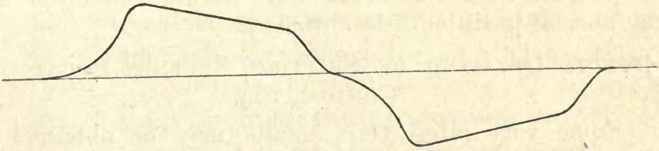

FIG. 71.—CURVE OF POTENTIAL ROUND THE COMMUTATOR. MACHINE WORKING AS MOTOR.

tips and pole faces. They form the most complete method of investigating the field distribution—one of the most important factors in dynamo design for producing sparkless running.

Regulation by Shifting Brushes.—In some cases it is necessary to provide for very great movement of the brushes. Thus for some special purposes the speed of a motor is regulated by moving the brush rocker round.

Motors specially designed for this, can be regulated, and even stopped and reversed, by the movement of the brush rocker alone.

Boosters, which are required to supply a variable voltage, are also sometimes regulated in this way in cases where the added voltage is very low. For regulating the voltage of the machine by means of a resistance in series with the field winding in the usual way, a very large and expensive resistance would be required in order to bring the voltage sufficiently low. Also at low voltages the field would be so weak as to be very unstable, and sparkless commutation would probably become impossible.

The best solution, both from the point of view of cost and satisfactory working, is therefore found in many cases to be a variable position of the brushes. The field is consequently maintained at a constant strength, and the voltage between the brushes is varied by varying the point on the armature at which they make contact.

In the case of machines to be employed in this way it is consequently sometimes necessary to determine the variation of voltage round the commutator as measured between the brushes when in various positions. This curve may in part be obtained on any machine without excessive sparking while running on no load. The general character of the curve so obtained would be similar to that shown on Fig. 62, where a point slightly to the right of the point where the brushes are shown, would represent the normal position of the brushes.

EFFECTS OBTAINED BY SHIFTING BRUSHES ROUND THE COMMUTATOR.

Some very interesting results may be obtained by observing the voltage between the brushes of a dynamo or motor when moved gradually round the commutator.

Such a series of readings may be made to give similar curves of induction round the commutator of any machine similar to those discussed above without the employment of any special instruments or auxiliary brushes.

On account of sparking these observations are more easily carried out on a motor, and a simple method of carrying out such a series of readings is described below.

In the experiment to be described a resistance is put in series with the motor armature to prevent the current becoming excessive when the motor comes to rest, and also to prevent the speed of the machine increasing too rapidly as the brushes are moved from their normal position.

Experiment XXV.—OBSERVATIONS OF THE EFFECT OF MOVING THE BRUSHES OF A MOTOR WITH CONSTANT EXCITATION.

DIAGRAM OF CONNECTIONS.

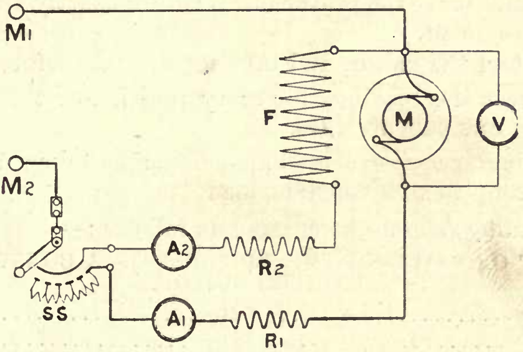

FIG. 72.

M_1 M_2	Supply mains.
M	Motor armature.
F	Field windings.
R_1	Constant resistance in armature circuit.
R_2	Adjustable resistance for keeping exciting current constant.
A_1	Ammeter for measuring armature current.
A_2	Ammeter for measuring exciting current.
V	Voltmeter for measuring armature voltage.
SS	Starting switch.

Connections.—Connect the motor to the source of supply through a starting switch, putting a constant resistance* in series with the armature. Since the exciting current is to be kept constant, insert in the motor field a variable resistance and ammeter. Put an ammeter in the armature circuit, and connect a voltmeter to the armature terminals.

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* The magnitude of this resistance must not be less than the number of ohms given by the fraction $\frac{\text{supply voltage}}{\text{maximum motor current}}$ in order that the full load current of the motor may not be exceeded.

Instructions.—Start the motor with its brushes in the normal running position, and adjust the exciting current to its normal value.

Take readings of the speed, armature current, and armature voltage.

Stop the motor and adjust the position of the armature until the tip of the brushes coincides with the division between two commutator segments. Then loosen the brush rocker and move the brushes forward by exactly the width of one segment.

Restart the motor, and take readings as before.

Repeat the readings for every position of the brushes between one pair of poles.

A similar series of readings should be taken with the motor coupled to a constant load.

Readings should be entered as follows:—

EFFECT OF SHIFTING THE BRUSHES OF A CONSTANTLY-EXCITED MOTOR.

Observer .... Date..........................
Motor No...................... Type ....
Normal output ....H.P., at......volts, and........revs. per minute.
Exciting current................amps.

No. of Segment from Normal Position.	Armature Current. Amps.	Armature Voltage. Volts.	Speed. Revs. per Min.

Curves should be plotted from the results showing (1) speed, (2) armature voltage, and (3) armature current for each position of the brushes. For this purpose the commutator segments should be marked off horizontally, the normal position of the brushes being in the centre of the paper and marked O.

These curves are shown in Fig. 73 as obtained in an actual experiment on a 2-pole Crompton motor having 30 commutator segments.

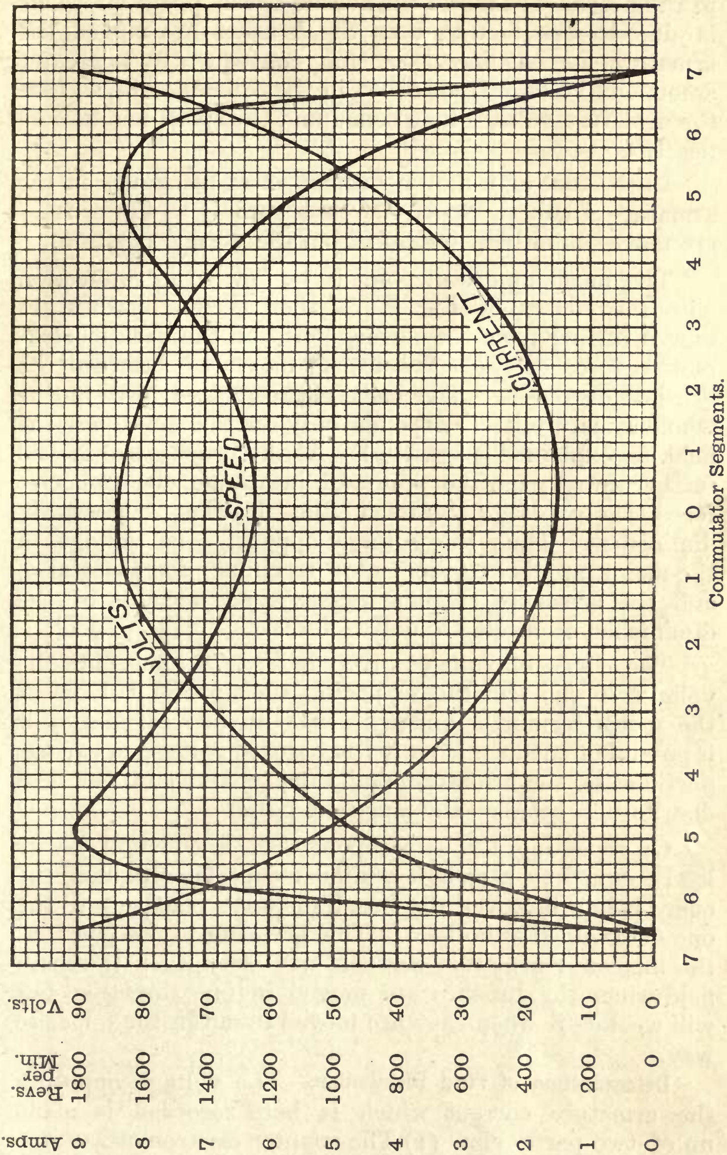

FIG. 73.—EFFECTS DUE TO MOVEMENT OF BRUSHES.

It will be seen that the speed curve is nearly horizontal in the neighbourhood of the normal brush position. This is due to the fact that as the brushes are moved the armature current increases, and consequently a greater amount of voltage is absorbed in the resistance R_1, so that the armature voltage is lessened and the speed maintained nearly constant.

In the case of a motor without extra resistance in the armature circuit the speed increases rapidly as the brushes are moved in either direction from the normal position.

The most important point to be noticed in connection with the curves in Fig. 73 is that as the brushes are moved further from the normal position the back electromotive force of the armature as measured between the brushes decreases. The back electromotive force of the whole armature itself depends only on the speed and the field, as explained (page 105). As the brushes are moved further away from the points of maximum electromotive force the voltage between the brushes necessarily diminishes. Thus the voltage opposing the voltage of the mains applied to the motor terminals decreases also, and the armature current increases on account of the diminished back electromotive force.

The curve of voltage given in Fig. 73 represents the voltage in the armature opposing the applied voltage at the motor terminals, and by a little further calculation it is possible to deduce from it the induced voltage in various portions of the armature, and thus to arrive at the field distribution between the magnetic poles.

On repeating the experiment with a constant heavy load coupled to the shaft a similar curve is obtained, the curve being, however, displaced sideways relatively to the one determined at no load. This is owing to the fact that the increased armature currents will strengthen the main field when the brushes are moved in one direction, but will weaken it when they are moved round in the opposite way.

Determination of Field Distribution.—The voltage opposing the armature current which is here recorded is made up of two parts, viz:. (1) The counter electromotive force generated in the armature conductors, due to their rotation in the magnetic field; (2) the voltage absorbed in

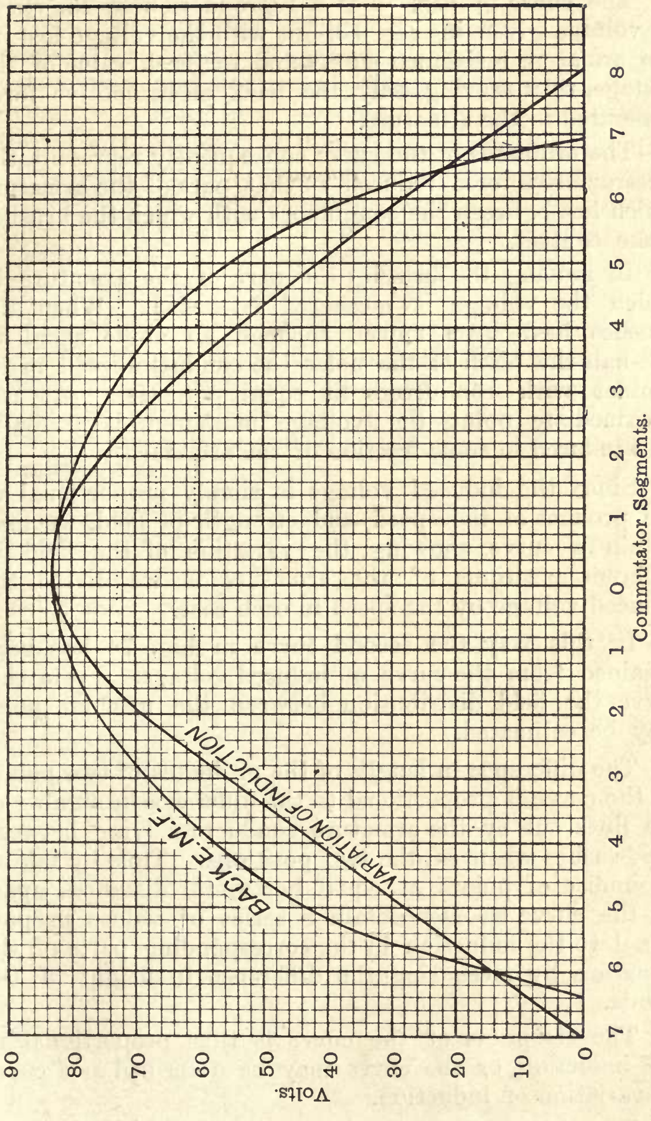

FIG. 74.—EFFECTS OF MOVEMENT OF BRUSHES.

the resistance of the conductors, numerically equal to the product of current and resistance.

The curve in Fig. 74 is a reproduction of the curve of voltage given in Fig. 73, but with the voltage lost in the armature resistance subtracted for each value of the voltage, thus leaving only the back electromotive force generated in the armature.

The ordinates of the curve consequently represent the electromotive force induced in that part of the armature which lies between the conductors with which the brushes make contact.

In moving the brushes the part of the armature in which the voltage is measured is varied. When the brushes have been moved through an angle equal to one-half the pitch of the poles the conductors will make contact with conductors at equal potential. At any intermediate point the voltage measured is virtually that induced in some fraction of the armature.

Since the induced voltage is simply proportional to the product of the speed and strength of field, we may obtain a curve showing the variation of the field in different positions of the armature if we divide the induced voltage by the speed in each case.

In this way the second curve in Fig. 74 has been obtained from the curve of induced voltage. From this curve the field distribution between the machine poles may be estimated.

The difference in length of the ordinates of two points on the curve is proportional to the difference in number of the lines cut by the armature conductors lying between the brushes when in the two positions. Thus by taking a number of points at equal horizontal distances apart on the curve we can obtain a series of values proportional to the induction in the corresponding parts of the armature by measuring the difference in height of the points.

The steepness of the curve is thus proportional to the induction, or the curve may be described as a curve of variation of induction.

The distorting effects of the armature current in these experiments may be kept small by reducing the applied voltage. This can be effected by increasing the resistance in series with the armature.

In the machine from which the curve in Fig. 73 was obtained there were 15 segments between the position of maximum and minimum voltage. Consequently in moving the brushes from segment to segment the voltage recorded was increased or diminished by the amount due to the magnetic field of one-fifteenth of the pole angle. If the field were uniform the increase of voltage would be the same in going from each segment to the next, and the curve would consist of straight lines. This is seen not to be the case except near the centre of the poles.

With a resistance in series with the armature sufficient to prevent the speed and current becoming excessive the machine may be regulated, stopped, and reversed by moving the brush rocker round. The ease with which this is performed is very striking, although the method is naturally not an efficient one.

CHAPTER XIII.

MOTOR GENERATORS AND BOOSTERS.

The following experiments are inserted with the object of enabling the student to make himself familar with one or two of the most important special uses to which dynamos are put, and which it is difficult for him to gain experience in by any other means than such experiments as those suggested.

BALANCING MACHINES FOR 3-WIRE SYSTEM.

Principle of the 3-wire System.—The 3-wire system of distribution is adopted for the sake of economy in the conductors. The three wires composing it are the equivalent of two circuits side by side, in which the outgoing wire of one circuit and the return wire of the other are replaced by a single wire. The current in this "middle" or "neutral" wire is the difference between the currents which would have been flowing in opposite directions in the two wires which it replaces. Since it can usually be arranged that the currents in the two circuits are nearly equal, the middle wire carries only a comparatively small current, and can be made of smaller section than the main conductors or "outer" wires.

Fig. 75 is a diagram illustrating the principle of the system. *A B*, *C D* are the main or "outer" conductors. *E F* is the "neutral" wire. *L*, *L*, *L* represent lamps or other apparatus supplied with current from the system.

The voltage between the outer wires is twice the voltage at which current is supplied to the consumers. Each consumer's circuit is connected to one of the outer wires and to the neutral wire.

The machines supplying the system are usually designed to give the voltage required between the outer conductors, and some means has therefore to be provided for dealing with the "out-of-balance current" in the neutral wire when the current taken from one of the main conductors exceeds the current taken from the other. This is usually accomplished by inserting at suitable points in the system either a pair of batteries or a pair of machines coupled together mechanically.

Where two machines are used, as indicated in the diagram, they are called *balancers*, since their function is to equalise or balance the load on the two main conductors.

When the currents taken from both outer wires are equal, there will be no return current in the middle wire. The balancing machines will then both run as motors taking current in series from the mains. As they run without load, they will run at a sufficiently high speed to make the current flowing through their armatures very small. They will only absorb the amount of power necessary to overcome the frictional and other losses in them.

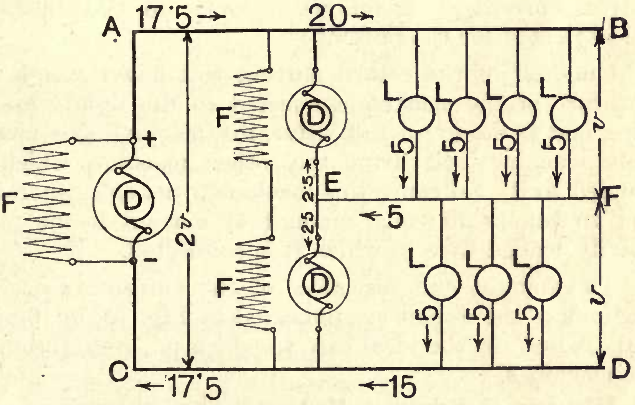

FIG. 75.—THREE-WIRE SYSTEM.

To make the balancing action clear, it is assumed that each branch circuit marked *L* in the diagram carries a current of five amperes. Since there are four such circuits connected to the + main, and only three circuits taking current from the − main, there is an out-of-balance current of five amperes flowing in the middle wire at the end nearest to the generator.

If this return current were not allowed to flow along the neutral wire, there would necessarily be the same current flowing from the neutral to the negative wire as flowed from the positive wire to the neutral wire. Since there are four parallel equal resistance connecting the + and neutral wires, and only three such resistances connecting the – and neutral wires, the total resistance on the positive side of the neutral wire is three-quarters of the resistance on the negative side. Hence the voltage between the – and neutral wires would be higher by one-third than the voltage between + and neutral. In general the difference in pressure between the more heavily loaded outer wire and the neutral wire tends to be less than one-half the voltage between the outers. The voltage between the middle wire and more lightly loaded outer tends to rise by the same amount. It is this difference of pressures which enables the balancing machines to operate, and it is this variation which they are intended to minimise. Referring to Fig. 75, where the return current is indicated as flowing through the balancing machines, the distribution of current is as follows if losses in the machines are neglected for the present :—

One-half of the return current will flow through the armature of the machine connected to the lightly loaded wire, and in doing so will drive the machine as a motor. This machine will drive the other machine which is coupled to it, and cause this machine to act as a generator, and to supply an equal amount of current to the more heavily loaded wire to which it is connected.

The amount and direction of the current in various portions of the circuit are indicated in Fig. 75 by figures and arrows, for the ideal case in which no losses occur in the machines.

Efficiency of Balancing Machines.—The purpose of the experiment next to be described is to find to what extent the losses in the balancing machines prevent the ideal condition represented in the diagram from being attained.

In the ideal condition, the difference of potential between each outer wire and the neutral wire is exactly half the difference of potential between the outer wires. As already explained, the machines will only act as balancers (*i.e.*, one taking current and acting as a motor to drive the other as a generator) when the voltage between one pair of wires is above the voltage between the other pair. For if the two voltages were equal, there would be nothing to make either machine act as a generator rather than the other.

An example will make clear what difference may be expected between the voltages of the two sides.

Suppose that with no current in the middle wire and equal voltages of 100 volts between the outers and the middle wire it is found that the current taken by the balancing machines is 1 ampere. Then the power taken by both of the machines in order to overcome the losses in them when running light is

$$2 \times 1 \text{ amp.} \times 100 \text{ volts} = 200 \text{ watts}$$

If now the loading in the system be altered so that the positive main is more heavily loaded, and an out-of-balance current of 2 amperes flows in the neutral wire, the current will divide at the balancers, and one ampere flow towards the positive main through one machine and the other towards the negative main through the other machine. There will thus be two equal and opposite currents in the machine connected to the positive wire, which will neutralise each other. This machine will therefore run without giving or receiving current. There will at the same time be 2 amperes flowing through the armature of the machine on the negative side in a direction such as to drive it as a motor.

The power expended in driving the two machines remains the same as before, but is all exerted in the armature of one machine. There will be a loss of voltage in the armature of the motor equal to the product of the current and the armature resistance. There must therefore be this amount of voltage at the motor terminals in excess of the pressure at the terminals of the other machine. This will be the least difference in pressure between the two sides of the system, which will enable the balancers to operate.

As the out-of-balance current increases, an increased current will flow through the armature of both machines, and the losses in each will increase. This will require a larger current in the motor machine to enable it to drive them. This, in turn, involves greater loss of voltage in the armature and greater difference in voltage of the sides of the 3-wire system.

The losses in the balancing machines will be made up of (*a*) the power supplied to the machine acting as motor in order to enable it to drive both machines, overcoming friction and internal losses, &c., (*b*) the loss of pressure in the armatures of both machines caused by the balancing current flowing through the armature resistance, a slightly greater drop always occurring in the motor armature, and (*c*) the current required for the excitation of both machines.

The following experiment is designed to illustrate the mode of action of a pair of balancers and to determine the variations in the voltage on each side of the neutral wire due to uneven loading.

Experiment XXVI.—Determination of the Regulation of a Pair of Balancers for a 3-wire System.

Diagram of Connections.

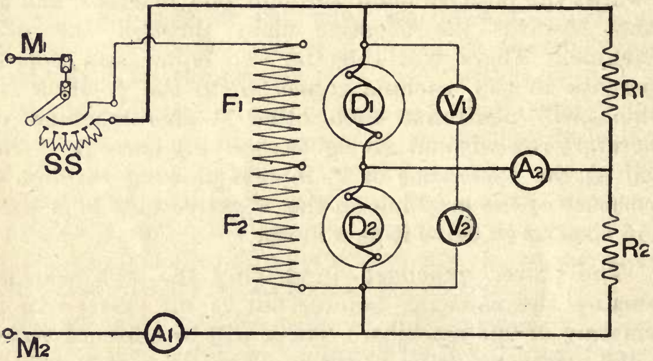

Fig. 76.—Test of 3-Wire Balancers.

M_1 M_2	Supply mains.
D_1 D_2	Balancer armatures.
F_1 F_2	Balancer field windings.
R_1 R_2	Resistances for varying load on the two main conductors.*
V_1 V_2	Voltmeters for measuring voltage on each side of neutral wire.
A_1	Ammeter for reading supply current.
A_2	Ammeter for reading out-of-balance current.
S S	Starting switch.

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* Frequently, instead of the two resistances, use is made of a single variable resistance having a movable contact. The contact divides the resistance into two parts, the middle wire is connected to the contact piece of the resistance, and the outer wires to the resistance terminals, thus making the two portions of the same resistance play the part of R_1 and R_2 in the diagram. By merely moving the handle of the resistance, the out-of-balance current is altered.

Connections.—The machines which are to act as balancers being coupled mechanically together, connect the armatures of the balancers in series, and also their field windings. Connect the armature and exciting circuits to the mains through a starting switch. Insert in the main circuit an ammeter. Connect two resistances for varying the load in series to the terminals of the two machines, connecting the common terminal of the resistances to the point joining the armatures. Insert an ammeter in this connection. Connect a voltmeter to the terminals of each machine.†

Instructions.—Keeping the current supplied to the system, as read on ammeter A_1, approximately constant, vary the relative magnitude of the load resistances R_1 and R_2 so as to gradually increase the current in the neutral wire.

Take readings of the speed, current supplied, current in the neutral wire, and voltage at the terminals of each machine.

Enter results as follows:

REGULATION OF BALANCERS FOR 3-WIRE SYSTEM.

Observer...................... Date.........................

Balancers No. .... Type ....

Capacity ....Amps., at ....volts. and ....revs. per min.

Revolutions per Minute.	Current Supplied.	Out-of-Balance Current.	Voltage + Side.	Voltage – Side.	Out-of-Balance Voltage.

Plot a curve showing dependence of out-of-balance voltage upon out-of-balance current.

Fig. 77 is a curve obtained in this way. The experiment was made with a pair of small machines having a high armature resistance of about ·35 ohms, the effect of which is clearly seen in the curve. The difference in voltage between the two sides of the system increases in direct proportion to the current flowing through the armatures of the two machines, as shown by the straight portion of the curve. The difference in voltage between the sides was ·12 volts when no current was returned to the machines by the middle wire.

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† In this case, as in one or two other experiments, a single voltmeter, with a suitable 2-way switch for changing over its connections, may be used instead of the two voltmeters shown in the diagram of connections.

Since the voltmeter current is so small as to be inappreciable, nothing is disturbed by such a change of connections.

The current taken by the machines from the mains when running without current in the neutral wire was 2 amperes. Hence the armature drop (which in a machine having such a high armature resistance is chiefly due to the resistance of the conductors) will be slightly more than 2 × ·35 = ·7 volts. Producing the straight portion of the curve back to cut the vertical axis, it will be found to cut it at about ·9 volts, which is nearly equal to the armature drop due to 2 amperes added to ·12 volts, the height of the first observation at no load.

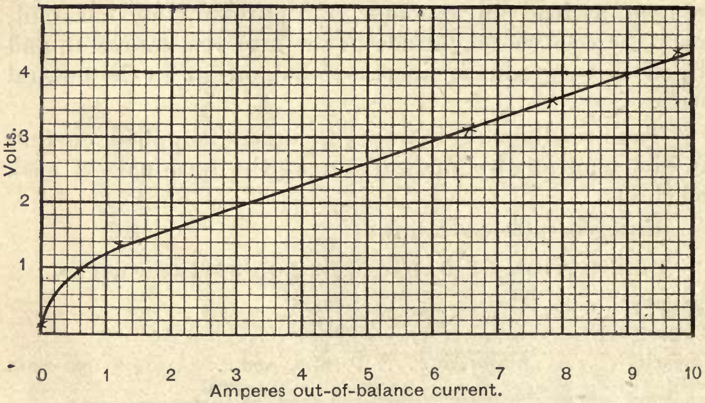

FIG. 77.—REGULATION OF 3-WIRE BALANCERS.

With 4 amperes out-of-balance current there will be approximately 4 amperes in the armature of the machine connected to the lightly loaded side, and acting as a motor. No current will then flow in the armature of the other machine. The armature drop in one machine is therefore ·35 × 4, and in the other nil. The armature drop has consequently increased on one side by 2 × ·35 = ·7 volts, and decreased on the other side by a similar amount.

Hence the difference in voltage between the two sides of the system must be approximately ·35 × 4 + ·9 = 2·3. This is seen to be true on the curve.

Similar reasoning may be applied to any other point on the curve.

Efficiency of Balancers.—By inserting an ammeter in one of the outer conductors, the efficiency of the *balanced* system at all loads may be measured.

The input is the product of the current and voltage of the supply. The output of the system will be the sum of the power usefully spent in the resistances connected to the outer wires—*i.e.*, the sum of the products of current and voltage taken separately for each side of the system.

$$\text{Efficiency} = \frac{\text{output}}{\text{input}}.$$

The efficiency of the *balancers* depends only on the out-of-balance current with which they have to deal, and not on the current in the outer wires. The power lost in their armatures is equal to the difference between the currents flowing in the two armatures multiplied by the voltage at the terminals of the machine which is acting for the time as motor. If both machines are acting as motors, the sum of the products of current and voltage taken for each armature gives the lost watts.

The efficiency of the combination

$$= \frac{\text{total power supplied to both armatures} - \text{watts lost}}{\text{total power in both armatures.}}$$

Alternative Connections of Field Windings.—In Fig. 76 both field windings are shown as supplied with the same current in series.

Frequently the windings are not connected in this way, but are separately connected to the opposite sides of the system. Thus the field windings of machine D_2 would be connected to the armature terminals of D_1, and the windings of D_1 would be connected to the terminals of D_2. The purpose of this cross-connection is to ensure a more accurate regulation of voltage by the variation in the speed of the machines which it produces.

For example, if D_2 is acting as motor, its field-windings will be connected to a lower voltage than the windings of D_1, since they are connected to the more heavily loaded side of the system. The field of D_2 is therefore weakened slightly, and the machine will endeavour to rotate faster, driving the generator D_1 with it and causing it to raise the voltage on account of the increased speed, and also because the generating machine will have a more highly excited field.

In order to illustrate the difference in regulation of the two ways of connecting the fields, Experiment XXVI. should be carried out with the fields connected first as shown in Fig. 76 and then cross-connected as just described.

In many cases occurring in recent practice *compound-wound* balancers are employed. In this case the machines have a shunt winding connected as shown in Fig. 76, and in addition have a series winding through which the armature current of each machine flows. The action of the out-of-balance current is then as follows : The current flowing through the machine acting as a motor has its field *weakened*, owing to the direction of the current flowing through it. The generating machine has its field strengthened. Thus the motor tends to rotate more rapidly, owing to the action of the series winding, while the generator voltage rises from the same cause. The number of series windings is determined by experiment as already described under "Compound Motors."

Frequently, in large stations the excitation of the balancing machines is regulated by hand, by means of a rheostat in the field circuit.

Efficiency of a Motor Generator.—A motor generator, or rotatory transformer, is a machine, or pair of machines, for converting current of a certain voltage into current having a different voltage, the two voltages being in a fixed ratio.

Motor generators may be operated by continuous or alternating currents, and may convert alternating currents into continuous, or vice versâ.

Here continuous-current machines are considered.

The motor generator consists essentially of two distinct armature windings wound either on to the same or separate armature cores. If on the same core, the two windings rotate between the same field magnets. If the armatures have separate cores, the apparatus is usually formed of two separate machines coupled together. One armature winding is supplied with current, and is thereby driven as a motor. The other winding has an electromotive force induced in it, and will give current, acting as a dynamo. If the two armatures rotate in the same field, or fields of equal strength, the voltage generated in the armature of the secondary, or generator, winding will bear the same ratio to the back electromotive force of the primary, or motor, armature as the number of secondary armature windings bears to the number of primary windings.

The back electromotive force of the motor armature would be equal to the electromotive force applied at the motor terminals, except for the losses in the armature and the frictional resistances, &c., opposing its rotation.

The ratio of the primary and secondary voltages is, therefore, approximately the ratio of the number of armature conductors. This approximation becomes closer as the losses in the machine become less.

It is of importance to determine the variation of two factors consequent on variations in the output of a motor generator. These are the ratio of transformation (*i.e.*, the ratio between primary and secondary voltage) and the efficiency of the apparatus (*i.e.*, the ratio of the power given out by the secondary to the power supplied to the primary).

Experiment XXVII.—TEST OF A CONTINUOUS-CURRENT MOTOR GENERATOR.

DIAGRAM OF CONNECTIONS.

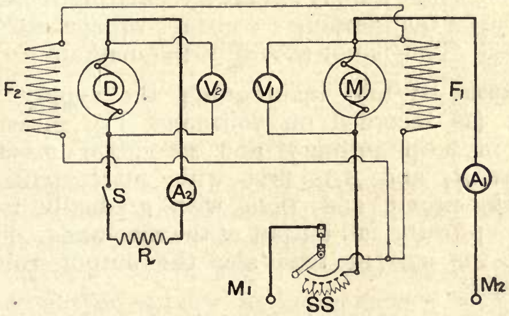

FIG. 78.—TEST OF MOTOR GENERATOR.

M_1 M_2	Supply mains.
M	Motor armature.
D	Generator armature.
F_1 F_2	Field windings.
A_1 A_2	Ammeters for measuring input and output current.
V_1 V_2	Voltmeters for measuring input and output voltage.
SS	Starting switch for motor.
R	Resistance for varying load of generator.
S	Switch for breaking generator circuit.

Connections.—Connect the motor side of the motor generator to the source of supply through a starting switch.

Insert in the main circuit an ammeter for measuring the current supplied. Connect a voltmeter to the motor terminals to measure the supply voltage.

Connect the generator terminals to a resistance for regulating the load, including in the circuit an ammeter and switch.

Connect a voltmeter to the generator terminals.

The two field windings may be connected to the supply mains through the starting switch, either in parallel (as shown in the diagram) or in series.

The voltage for which they are designed must determine which method is to be adopted.

Include in the supply circuit a regulating resistance, if necessary, for maintaining a constant voltage at the motor terminals. (This is not shown in the diagram.)

Instructions.—While maintaining the supply voltage constant (as recorded on voltmeter V_1), measure the current in both primary and secondary circuits (on ammeters A_1 and A_2), first with no current in the secondary circuit and then with gradually increased currents up to the full output of the machine. For each value of the current read also the output voltage on voltmeter V_2.

Enter the results as in the following table.

TEST OF A MOTOR GENERATOR.

Observer .... Date ....
Motor Generator No. .... Type ....
Supply voltage .... Output voltage ....
Output current......................amps., at......................revs. per min.

Input.			Output.			Efficiency per cent.	Ratio of Transformation.
Volts.	Amperes.	Watts.	Volts.	Amperes.	Watts.		

Plot curves showing (1) The dependence of the ratio of transformation on the output. The ratio of transformation is the ratio of primary to secondary voltage. (2) The dependence of the efficiency on the output.

$$\text{The efficiency per cent.} = \frac{\text{power given out}}{\text{power supplied}} \times 100.$$

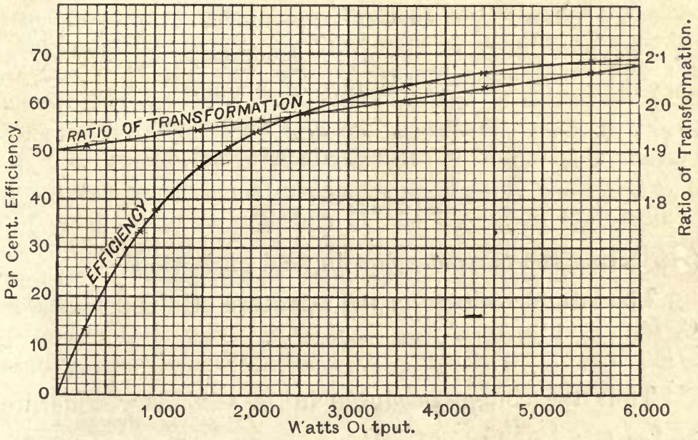

FIG. 79.—TEST OF MOTOR GENERATOR.

In the case of both input and output the power is measured in watts, which are obtained by multiplying the current (in amperes) by the voltage.

The curves given in Fig. 79 show the results of a test carried out on a 6-kw. motor generator with a ratio of transformation of 200 to 100.

The efficiency curve is of the usual form, showing a somewhat low maximum efficiency of 69 per cent. at full load. The low efficiency is partly due to the fact that the motor generator consisted of two separate machines coupled together, and having four bearings and two separate field windings.

The curve showing the ratio of transformation is practically a straight line. It is inclined to the horizontal owing to the fact that the loss of voltage in the armature windings increases in proportion to the load. The secondary voltage, consequently, decreases in proportion to the load, and the ratio $\frac{\text{primary voltage}}{\text{secondary voltage}}$ becomes greater.

The loss of voltage at any load due to armature resistance is

$C_1 R_1$ in the primary winding (neglecting armature magnetic reaction and other minor losses),

$C_2 R_2$ in the secondary winding,

Where C_1 = current in primary.
C_2 = ,, secondary.
R_1 = resistance of primary.
R_2 = ,, secondary.
K = ratio of transformation.

and since $\frac{C_1}{C_2} = \frac{1}{K}$

(neglecting the current spent in field excitation).

The loss of voltage in the armature of the primary is $\frac{C_2 R_1}{K}$.

Thus the voltage produced in the secondary armature is $\frac{1}{K}\left(V - \frac{C_2 R_1}{K}\right)$

and the voltage measured at the terminals of the secondary is $\frac{1}{K}\left(V - \frac{C_2 R_1}{K}\right) - C_2 R_2$.

$$= \frac{V}{K} - C_2\left(\frac{R_1}{K^2} + R_2\right)$$

If there were no losses in the armatures the secondary voltage would be $\frac{V}{K}$.

Hence the expression $C_2\left(\frac{R_1}{K^2}+R_2\right)$ represents the drop in voltage due to the armature resistances.

Boosters.—Boosters are auxiliary machines employed to increase or regulate the pressure at some point of a distribution system supplied with current from some independent source. They may also be used to add to the normal voltage of the line for special purposes, such as the charging of accumulators when the line voltage is not sufficiently high for the purpose. They are frequently used to increase the voltage at a distant point in a system supplied by feeders in order to make good the loss of pressure sustained by the current in flowing through the resistance of the feeders.

The general mode of action of a booster is as follows:

The current flowing in the circuit whose pressure is to be altered is sent through the armature of the booster, the construction of which is similar to an ordinary dynamo. The booster is driven mechanically by a motor or steam engine. If its direction of rotation is such that the electromotive force generated in the armature of the booster is in the same direction as the electromotive force of the circuit, then the booster will add the voltage generated in its armature to the voltage of the source of the current. The pressure of the circuit is then said to be "boosted up." The machine is called a "positive booster," under these conditions. If the direction of rotation of the booster armature be reversed, the electromotive force generated will oppose that of the source, and the voltage of supply is then said to be "boosted down," and the machine operates as a "negative booster."

A machine may be made to act positively or negatively, or to allow the current to flow through its armature without change of voltage, by altering the direction or amount of the exciting current in its field windings. It is in the means of regulating the direction and strength of the field that most of the differences occur in the boosters as applied to different purposes.

Two experiments are given to illustrate two methods of regulation.

Separately Excited Booster.—The method of exciting a booster described in the first experiment is often of use in a dynamo test house, as it affords a means of obtaining any required voltage either above or below the available pressure of the mains without the necessity of employing a motor generator or special dynamo to give the output required. Practically it consists in putting the voltage of an auxiliary generator in series with the voltage of the mains.

Experiment XXVIII.—Test of a Separately-excited Booster.

Diagram of Connections.

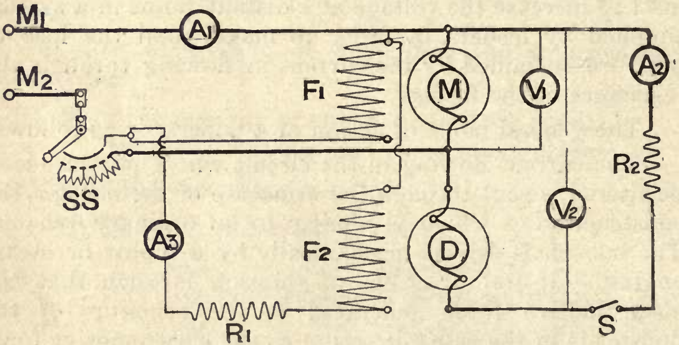

FIG. 80.—SEPARATELY EXCITED BOOSTER.

M_1 M_2	Supply mains.
M	Motor armature.
D	Booster armature.
F_1 F_2	Field windings of motor and booster.
R_1	Resistance for regulating field excitation of booster.
R_2	Resistance for varying main current.
A_1	Ammeter for measuring current supplied.
A_2	Ammeter for measuring load current.
A_3	Ammeter for measuring booster exciting current.
V_1	Voltmeter for measuring voltage of supply.
V_2	Voltmeter for measuring voltage of load circuit.
S	Switch for breaking load circuit.
S S	Starting switch for motor.

NOTE.—The above diagram shows the booster driven by a motor. It may equally well be driven by a steam or other engine. In that case the main current is simply sent through the armature of the booster from brush to brush. The starting switch and other connections for the motor are then unnecessary.

Connections.—Couple the booster to a motor or other means of driving. Connect one of its terminals to one of the mains supplying the current at the pressure which is to be altered. If the pressure is to be increased by the booster, the positive brush of the booster must be connected to the negative supply main, or the negative brush to the positive main. If the pressure is to be reduced, brush and conductor of the same sign must be joined. Connect the other terminal of the booster to the load circuit to be supplied with current at the altered voltage. The supply main which is not connected to the booster forms the other conductor to supply the load circuit.

Insert an adjustable resistance in the booster field circuit to regulate the voltage added or subtracted.* Employ a variable resistance in the load circuit to regulate the load current. Put in series with it an ammeter and switch.

Insert an ammeter in the supply circuit, and connect voltmeters across the supply and load circuits respectively, or arrange a single voltmeter with a 2-way switch to read both voltages. Put an ammeter in the booster exciting circuit.

Instructions.—Drive the booster at full speed; then adjust its exciting current by means of the resistance R_1 until the required voltage in the load circuit is obtained, as read on voltmeter V_2. Maintaining this voltage constant (by further alteration of R_1 when required), close the switch S in the load circuit and gradually increase the load current by decreasing the resistance R_2. For each value of the load, read the current and voltage in the supply circuit on A_1 and V_1. Read the load current on A_2, and the speed; also the exciting current on ammeter A_3.

Enter observations as in the table on the following page.

The figures in the last column are obtained by dividing the output by the input and multiplying by 100, thus—

$$\text{Efficiency} = \frac{\text{Watts output}}{\text{Watts input}} \times 100.$$

---

* This adjustment can also be made by means of resistance in the field circuit of the driving motor, by which the speed of the machines may be varied. The higher the speed of the booster the higher will be its voltage.

TEST OF SEPARATELY-EXCITED BOOSTER.

Observer........................ Date ....
Booster No. .... Driven by..........................
Output................ Amps. .... Speed..............
Voltage of supply................ Voltage in load circuit ....

Revolutions per Minute.	Booster Exciting Current	Input.			Output.			Efficiency per Cent.
		Volts.	Amps.	Watts.	Volts.	Amps.	Watts.	

The results when plotted to compare output and efficiency give a curve similar to the efficiency curve shown on Fig. 79 for a motor generator.

A second curve should be plotted comparing the exciting current required to maintain the voltage constant with the current in the armature of the boosting machine.

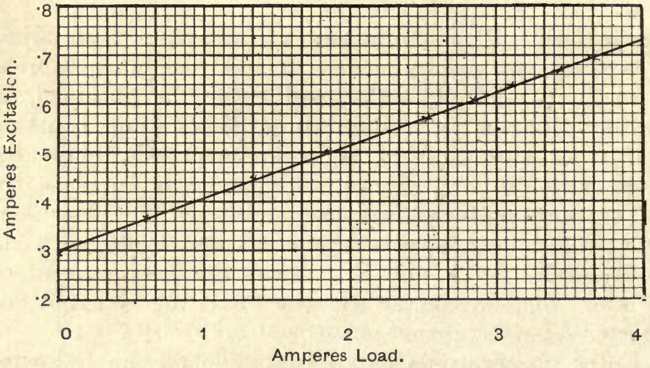

FIG. 81.—EXCITATION OF SEPARATELY EXCITED BOOSTER TO MAINTAIN CONSTANT VOLTAGE.

Such a curve is shown on Fig. 81, and it will be seen to be a straight line. This is because the saturation of the magnetic circuit is taken low, and the increase of exciting current is almost exactly in direct proportion to the loss of voltage occasioned by armature reactions at increasing loads.

With more highly saturated fields the curve would resemble that shown in Fig. 18, page 64, the lower portion of which is straight, while the upper part curves upwards, showing that, as the fields become fully saturated, a stronger current becomes necessary to produce the required increase in magnetic lines.

The curve shown in Fig. 81 gives important information where it is desired to vary the excitation automatically so as to produce a constant voltage for all values of the main current.

Usually it will be necessary to design the booster so as to give this curve as a straight line in order that an excitation proportional to the load shall be able to maintain the voltage constant.

According to the conditions under which the booster is to work, it may be necessary to vary the experiment in various ways.

The voltage of supply may vary with the load, while it is desired to keep the output voltage constant.

The voltage of supply may be constant while it is necessary to vary the voltage of the load circuit—for instance, in order to charge a battery, the charging voltage of which varies, but is always slightly higher than its discharge voltage.

It may also be necessary to determine how the booster voltage alters with varying loads when the exciting current is kept at a constant value.

Sometimes the exciting current of the booster, or the exciting current (and consequently the speed) of the driving motor, are made to vary automatically by being connected to some point in the distribution system, of which the voltage varies.

In such cases it may be necessary to determine beforehand the variation in voltage produced by given variations in the exciting current.

Series-wound Booster.—The type of booster which forms the subject of the next experiment is sometimes used for regulating the pressure at the end of a pair of feeders supplying current from a central station to a distant part of a distribution system at which the voltage is to be kept constant.

The loss of voltage in the feeders is proportional to the strength of the current. It is therefore necessary for the booster to give to the circuit an additional voltage equal to the loss in the feeders, *i.e.*, proportional to the current in the feeders.

This is done by exciting the field of the booster by the current in the feeders, which flows through the field windings and armature in series. The exciting current is thus proportional to the voltage required from the booster. It is consequently necessary that, as far as possible, the strength of the field should increase in proportion to the exciting current. This can only be attained by employing a low degree of saturation for the magnetic circuit, so that the working current shall produce an excitation corresponding to the straight portion of the magnetisation curve. (See Fig. 12, page 39.) For the straight portion of the magnetisation curve, the increase in voltage of the machine is proportional to the excitation. Armature reactions will prevent an exact proportionality between voltage and excitation from being maintained. To allow for this, and for the fact that the magnetisation curve is not exactly straight, extra turns have to be wound upon the field, which will cause the voltage to increase rather too rapidly at light loads and less at full loads, but will maintain the *average* voltage as nearly constant as possible.

Experiment XXIX.—VOLTAGE REGULATION BY SERIES BOOSTER.

DIAGRAM OF CONNECTIONS.

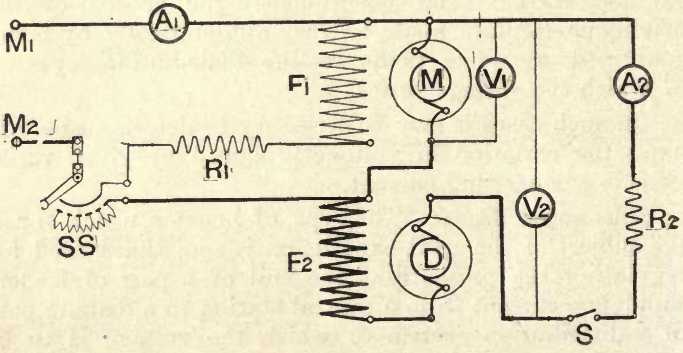

FIG. 82.—REGULATION BY SERIES BOOSTER.

M_1 M_2	Supply mains.
M	Motor armature.
D	Booster armature.
F_1 F_2	Field windings of motor and booster.
R_1	Resistance for regulating excitation of motor.
R_2	Resistance for varying main current.
A_1	Ammeter for measuring current supplied.
A_2	Ammeter for measuring current in load circuit.
V_1	Voltmeter for measuring voltage of supply.
V_2	Voltmeter for measuring voltage of load circuit.
S	Switch for breaking main circuit.
S S	Starting switch for motor.

NOTE.—The above diagram shows the booster driven by a motor, for which the connections are shown. It may be driven by a steam or other engine. In such a case the connections will be as shown, except that the motor connections must be omitted, including R_1, F_1, and M.

Connections.—Couple the booster to a motor or other engine for driving it at a constant speed.

Connect the field winding of the booster in series with its armature, and connect the machine in the main circuit so as to be in series with the load resistance, a switch and an ammeter for measuring the load current. Care must be taken to connect the negative booster terminal to the positive main conductor of the circuit, so that the booster when excited by the main current may *add* to the voltage of the circuit.

Connect a voltmeter to read the pressure of the current supplied, and a second voltmeter to measure the voltage increased by the booster and supplying the load. (Both readings may be made on a single instrument with a 2-way switch for making connection to either terminal of the booster.) If driven by a motor, a regulating resistance should be put in the motor field circuit to allow of speed regulation. If the combined efficiency of booster and motor is required, an ammeter should be inserted in the common lead supplying both the motor and load.

Instructions.—Drive the booster at normal speed. Vary the current in the load circuit by alteration of R_2. For each value of the load read voltage of supply (on V_1), the voltage applied to the load circuit (on V_2), and the load current (on A_2).

If the efficiency of the whole apparatus is required, read also the current supplied (on A_1).

The speed is to be kept constant throughout.

Readings should be entered as follows:—

TEST OF SERIES-EXCITED BOOSTER.

Observer...................... Date ....
Booster No. .... Driven by.....................
Output..................amps. Speed..........................
Voltage of supply.......... Range of increase of voltage..........

Revolutions per Minute.	Input.			Output.			Efficiency per cent. $\frac{V_2\times A_2}{V_1\times A_1}\times 100$	Booster Voltage $V_2 - V_1$
	Volts. V_1	Amps. A_1	Watts. $V_1\times A_1$	Volts. V_2	Amps. A_2	Watts. $V_2\times A_2$		

From the results a curve should be plotted showing the efficiency of the set at various values of the load.

A curve should also be plotted comparing the increase of voltage due to the booster with the load current. This has been done in Fig. 83.

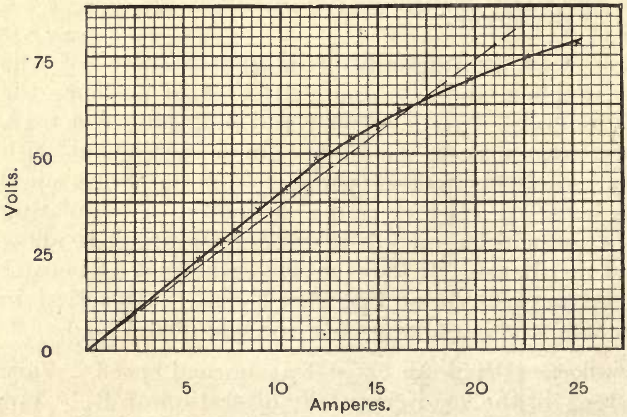

FIG. 83.—VOLTAGE REGULATION BY SERIES BOOSTER.

The curve is straight for low values of the load, but tends to the right as the magnets begin to get saturated by the heavier current. In the case illustrated by the Fig. 83, an approximately uniform increase of voltage proportional to the load is obtained up to 20 amperes, the increase being 3·72 volts for each ampere of load. Since the saturation causes the curve to indicate a rather less increase at higher loads, the magnet windings are chosen to give a rather greater increase at low loads, so that the *average increase* in voltage is obtained throughout the entire range of load.

The dotted line shows the increase of voltage desired, to which the actual values approximte on the average.

The requisite number of ampere-turns to produce any desired increase in voltage is found from a magnetisation curve as previously explained in the case of a shunt dynamo.

INDEX.

PAGE

Ampere-turns, Determination of ... 46
Ampere-turns, Determination of, to Maintain Constant Voltage ... 62
Arc Lighting Dynamo, Characteristic of ... 87
Armature Drop ... 50
Armature Reaction ... 50
Armature Resistance, Measurement by Voltmeter and Ammeter ... 6
Armature Resistance, Measurement by Comparison of Deflections ... 8
Armature Resistance, Measurement by Potentiometer ... 12
Armature Resistance, Measurement by Thomson Bridge... 16
Armature, Voltage Round ... 187, 191
Armature, Nature of Curves of Voltage Round ... 195

Back E.M.F. in Motor ... 105
Balancers for 3-wire System... 211
Balancers, Connection of Field Windings ... 217
Boosters ... 223
Boosters, Test of Separately-excited ... 224
Boosters, Test of Series ... 228
Brake Test of Shunt Motor ... 124, 127
Brake Test of Series Motor ... 131
Brush Friction Losses ... 166
Brushes, Effects of Shifting... 202

Calibration Curve ... 3
Characteristic, Motor ... 134
Characteristic of Separately-excited Dynamo ... 58
Characteristic of Series Dynamo ... 81
Characteristic of Shunt Dynamo ... 71
Characteristic, External and Internal ... 74
Characteristic, Load, of Shunt Motor ... 126, 127
Characteristic, Load, of Series Motor ... 131
Combined Engine and Dynamo Sets, Testing of ... 174

PAGE

Compound Dynamo ... 94
Compound Dynamo, Long and Short Shunt Connections ... 96
Compound Dynamo, Determination of Windings ... 100
Compound Motor ... 137
Compound Motor, Determination of Windings for ... 138
Compound Windings, Determination of ... 100
Conductivity Characteristic of Shunt Dynamo ... 76
Conductivity Characteristic of Series Dynamo ... 85
Constant Speed Motor ... 138
Core Losses ... 166, 171
Counter E.M.F. in Motor... 105
Cradle Dynamometer ... 141
Critical Current for Series Dynamo ... 92
Critical Resistance for Series Dynamo ... 89
Critical Speed of Motor ... 122
Cumulative Winding of Motor 140

Density, Magnetic ... 47
Differential Winding for Motor ... 138
Direction of Rotation in Dynamo and Motor ... 122
Distortion of Field by Armature Current ... 56
Distribution of Field, Determination of ... 187, 206
Drop in Armature ... 50
Dynamo, Efficiency Tests of 144
Dynamo, Efficiency Tests of Two Machines Coupled in Parallel ... 148
Dynamo, Efficiency Tests of Two Machines Coupled in Series ... 154
Dynamo, Efficiency Test by Swinburne's Method ... 158
Dynamo, Electromotive Force in ... 23
Dynamo, Separation of Losses in ... 165
Dynamometer, Cradle ... 141
Dynamometer, Dynamo as ... 142
Dynamometer, Transmission 140
Dyne ... 23

PAGE
Eddy Current Losses...... 166, 171
Efficiency of Combined Plant 174, 178
Efficiency of Motor 124
Efficiency, Swinburne's Test of Dynamo 158
Efficiency Tests of Dynamo ... 144
Efficiency Test of Two Coupled Dynamos Connected in Parallel 148
Efficiency Test of Two Coupled Dynamos Connected in Series 154
Electromotive Force in a Dynamo 23
Electromotive Force, Value of 25
E.M.F., Back, in Motor 105
Excitation of Motor 107
Excitation, Power Spent in ... 48
Excitation, Variation in, to Change Voltage of Dynamo 48
Exciting Current, Variation of, to Maintain Constant Voltage 62
External Characteristic, Compound Dynamo 97
External Characteristic, Series Dynamo 83
External Characteristic, Shunt Dynamo 74

Flux Through Armature 28

Hints for Testing 1
Hopkinson Test of Two Coupled Dynamos Connected in Parallel 148
Hopkinson Test of Two Coupled Dynamos Connected in Series 154
Horse-power Curves 78
Hysteresis 40
Hysteresis Losses in Dynamo 166, 171

Induction Curves of Armature 195, 206
Insulation, Test of Dynamo... 182
Internal Characteristic, Compound Dynamo 99
Internal Characteristic, Series Dynamo 85
Internal Characteristic, Shunt Dynamo 74

Lead of Brushes 54
Leakage, Magnetic 43
Leakage, Determination of Magnetic 185

PAGE
Lines of Force in Armature... 28
Long and Short Shunt Excitation in Compound Dynamo 96
Losses, Separation of, in Dynamo 165, 171
Magnet Winding, Resistance of 17
Magnet Winding, Temperature Increase in 18
Magnetic Brake 127
Magnetic Circuit 30
Magnetic Density 47
Magnetic Flux through Armature, Curves of 195
Magnetic Leakage 43
Magnetic Leakage, Determination of 185
Magnetisation Curve 31
Magnetisation Curve, Calculation of 33
Magnetisation Curve, Determination of, at no Load 38
Magnetisation Curve, Determination of, under Load ... 65
Magnetisation Curve, Influence of Air Gap on 44
Magnetomotive Force 34
Motor, Brake Test of Shunt... 127
Motor, Brake Test of Series... 131
Motor, Cause of Rotation of Armature 104
Motor Characteristic 134
Motor, Compound 137
Motor, Counter E.M.F. in Armature 105
Motor, Efficiency of 124
Motor Generator, Efficiency of 218
Motor, Methods of Excitation 107
Motor, Relation between Speed and Voltage............ 116
Motor Speed Regulation 110
Motor Starting Switch 108
Motor, Torque of 105
Motor, Variation in Speed with Variable Excitation ... 111

Ohmic Drop in Armature...... 50
Over Compounding 95

Permeability 30
Potentiometer, Measurement of Armature Resistance by 12
Power Curves 78
Reactions, Armature 50
Reactions, Armature, Magnetic 52
Regulating Resistance for Motor 114, 115
Regulation of Motor Speed ... 110

PAGE
Reluctance 32, 44
Residual Magnetism 40
Resistance Characteristic of Shunt Dynamo 77
Resistance Characteristic of Series Dynamo 85
Resistance of Armature, Measurement of 6
Resistance of Armature by Voltmeter and Ammeter ... 6
Resistance of Armature by Comparison of Deflections... 8
Resistance of Armature by Potentiometer 12
Resistance of Armature by Thomson Bridge 16
Resistance of Field Windings, Measurement of 17
Resistance of Field Windings, Variation with Temperature 18
Resistance, Regulating, for Shunt Winding 18
Resistance, Determination of Temperature by Increase of 19
Rotation, Direction of, in Dynamo and Motor 122

Series Dynamo 81
Series Dynamo, Condition for Self-excitation 89
Series Motor, Speed Curves of 135
Series Motor, Test of 131
Series Winding in Compound Dynamo, Determination of 100
Short Shunt Excitation for Compound Dynamo 96
Shunt Motor, Test of 127
Shunt Winding, Resistance of 17
Shunt Winding, Temperature Increase in 18
Shunt Wound Dynamo 68
Shunt Wound Dynamo, Relation between Voltage and Speed in 69
Sparking at Commutator 56
Speed and Voltage, Relation between, in a Separately-excited Dynamo 26
Speed and Voltage, Relation between, in a Shunt Dynamo 69
Speed and Voltage, Relation between, in a Series Dynamo 82, 87
Speed, Critical, of Motor 135
Speed Curves of Series Motor 135

PAGE
Speed, Effect of Variation of Voltage upon, in Motor...... 116
Speed, Regulation of, in Motor 110
Speed Variation with Excitation 111
Starting Switch 108
Steam Consumption, Test of... 174, 178
Swinburne's Efficiency Test of Dynamo 158

Temperature, Permissible Increase of 173
Temperature, Variation of Resistance with 18
Temperature, Determination of, by Increase of Resistance 19
Test of Series Motor 131
Test of Shunt Motor 127
Test of Two Coupled Dynamos 147
Test of Two Coupled Dynamos Connected in Parallel 148
Test of Two Coupled Dynamos Connected in Series 154
Test, Swinburne's, of Dynamo 158
Testing of Combined Engine and Dynamo Sets 174
Tests of Dynamo Efficiency ... 144
Three-wire System 210
Three-wire System, Test of Balances for 214
Torque of Motor 105
Total Characteristic, Compound Dynamo 99
Total Characteristic, Series Dynamo 85
Total Characteristic, Shunt Dynamo 74
Transmission Dynamometer .. 140

Voltage, Effect of, upon Speed in Motor 116
Voltage of a Dynamo 25
Voltage, Variation with Speed 25
Voltage, Variation with Speed, Separately-excited Dynamo 26
Voltage, Variation with Speed, Shunt Dynamo 69
Voltage, Variation with Speed, Series Dynamo 82, 87
Voltage Round Armature...... 187
Voltage Round Armature, Nature of Curves 195

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